REMARKS

This Amendment is submitted preliminary to the issuance of an Office Action in the present application and in response to the Official Action of February 7, 2008.

Record is also made of an interview between applicant's representative and the Examiner which took place on August 6, 2008 in which the undersigned acknowledged the change in Examiner's, since the previous Examiner had left.

The following remarks are thus in response to the last Office Action directed to claims 54,56-60,66-71, 75 and 77-86 which are pending in the application.

REJECTION OF CLAIMS 54, 56, 60, 66-71, 77-84 AND 86 UNDER 35 U.S.C. §112, SECOND PARAGRAPH

Claims 60, 69, 75, 80, 83 and 85 were amended to eliminate certain formal objections and rejections thereof. No claims were cancelled.

With respect to claim 83 on page 3 of the Official Action, the Examiner has outlined the withdrawals of the rejections from the last Office Action. Under D1, the Examiner rejects the claims again based on the limitation "the monomers" in line 6 and 7. Applicant has amended the claim to eliminate any confusion on this point by deleting the repetition of "monomers". It is believed that this clarifies the claim and that the amendment avoids the rejection.

With respect to "the linking reaction", applicant has amended claim 75 to clearly state "a linking reaction" and further in claim 75 explain the linking. Claim 60 thus refers to "the linking reaction" of claim 75 and there should be now no confusion as to what is being linked since it is clear form the context of the claim. It is believed that the amendment avoids the rejection.

With respect to claims 80, 83 and 85, these claims were amended to read "covalently linking" on order to avoid confusion of "the linking". It is believed that the amendment avoids the rejection.

REJECTION OF CLAIMS 54, 56, 60, 66-71, 77-84 AND 86 UNDER 35 U.S.C. §112, FIRST PARAGRAPH

The Examiner has rejected the claims for lack of enablement. As grounds the Examiner states the specification states that the magnetic particles are required citing various pages and paragraphs of the specification. Applicant traverses this interpretation. The specification does not state on pages 28 and 29 no in paragraphs 26 and 27 such a requirement. Paragraphs 37 and 37 clearly state this as another preferred embodiment but does not recite it to be a requirement.

The Examiner has refused to accept that applicant's method does not require two-component toners and magnetic particles and that the "magnetic" component is a best mode embodiment. Applicant submits that at the time of the invention one component toners were described as early as 1937 and were certainly in circulation in 1998, the filing date of the application. Submitted herewith is 1988 reference: L. B. Schein, Electrography and Development Physics, Springer Verlag Editor Helmut Lotsch: ISBN 3-540-18902-5 (1st Edition 1988).

In its Introduction this reference states......." work on monocomponent systems is reviewed in chapters 8 and 9.....; liquid development systems are descried in Chap. 10. The reference is supplied.

Moreover, chapter 1.1. of this book gives an overview over the technical history of the process of electrophotography, an invention that dates back to the year 1937:

- Chapter 1.1 Technical History, third paragraph: The two ideas that Carlson brought together in 1937 were: (1) the formation of an electrostatic latent image using photoconductivity to selectively discharge a surface charged insulator, and (2) "development" of this latent image by dusting with powders charged electrostatically.
- Chapter 1.1 Technical History, page 5, lines 6- 10: Development to create a real image was accomplished by sprinkling a fine dust or powder from a can having a cloth or fine wire screen closing its mouth. Pulverized resins were preferred (because of fusing requirements) but gum copal, gum sandarac,

ordinary rosin, sealing wax, dyed lycopodium powder, talcum powder, carbon dust, etc. were also used. The dusted plate was then subjected to a "... gentle draft of air by blowing the breath on it or directing air from a nozzle of a suitable blower against the dusted surface to blow off all loose powder not held on the surface by electrostatic attraction."

- Chapter 1.1 Technical History, page 7, lines 34- 37: ... some of the earliest work on novel monocomponent development systems and organic photoreceptors was begun during this period. ...
- Chapter 1.1 Technical History, paragraph flanking page 11 and 14 (with Table 1.1 in between): ... Another contribution, again from Japanese companies, was announced at the 1985 IEEE-IAS (Industrial Application Society) annual meeting in Toronto. Both Ricoh and Toshiba recognized the potential benefits of monocomponent development with nonmagnetic toner, such as lower toner manufacturing cost and the potential for better colors that could be obtained with toner loaded with magnetic material.

In other words: as early as the 1940s numerous variants of toner deposition with numerous materials were known that didn't involve magnetic particles or triboelectric charging; and by the year 1988 the existence of different kinds of toners was so well known to the scientific community that it was mentioned in the introduction and in the blurb of a textbook. In addition, least in the late 1980s a plethora of different commercially available laser printers and laser copiers existed that used many different kinds of toners (see e.g. Chapter 1.1 Technical History, Table 1.1; Chapter 1.3 Printer Market, Table 1.4; Ricoh's commercially available PC-6000 uses monocomponent, non-magnetic toner particles).

The textbook describes in chapter 3 the many different variants of "development", i.e. the different procedures to charge toner particles and to deliver them to the 2D electrostatically patterned image drum:

- Chapter 3.3 Descriptions, 3rd paragraph on page 59 to page 60: A description of different monocomponent development systems is given;

- Chapter 3.3 Descriptions, 3rd paragraph flanking pages 60 and 61 and Fig. 3.9: A description of different monocomponent development systems is given without magnetic constituents;
- Chapter 3.3 Descriptions, 3rd paragraph on page 61 to page 62 and Fig. 3.10: A description of a liquid development systems is given without magnetic constituents;

The textbook describes in chapter 8 the many different variants of "monocomponent development systems", i.e. the different procedures to charge monocomponent toner particles and to deliver them to the 2D electrostatically patterned image drum. It is quite easy, e.g. to incorporate magnetic properties into monocomponent particles:

- Chapter 8, 2nd paragraph on page 187: "... Magnetic properties, if needed, are obtained by adding magnetite, γ-Fe_3O_4, or similar materials, with 50% loading not uncommon. ..." ;

The same page states that a large variety of different charging methods exist, i.e. many procedures were known already in 1988 to produce, charge, and deliver toner particles to a 2D surface patterned with electrostatic charges:

- Chapter 8, 4th paragraph on page 187: "A surprisingly large variety of charging methods have been identified and incorporated into monocomponent development systems. ..." ;
- Chapter 8.3 Contact Charging pp194: "Triboelectric or contact charging has become the most monocomponent charging method." This sentence is followed by a number of commercially available copy machines that use this method;
- Chapter 8.3 Contact Charging p195, see also Fig. 8.12: "Ricoh has discussed (references 8.15-17) a system, shown in Fig. 8.12, to charge nonmagnetic monocomponent toner triboelectrically."
- Chapter 8.3 Contact Charging p198, paragraph below Fig. 8.15 see also Fig. 8.15: "At the same meeting at which Ricoh presented their results (see

above) Hosoya et al. from Toshiba (reference 8.18) presented their ideas for charging nonmagnetic insulating toner. Their apparatus is shown in Fig. 8.15."

- Chapter 9.6 Nonmagnetic, Insulative Toner p221, first paragraph above Fig. 9.15 see also Fig. 9.16: "In 1985 at the IEEE-IAS Conference in Toronto both Ricoh (references 9.21, 28, 29) and Toshiba (references 9.20, 30) announced a nonmagnetic insulating toner monocomponent development system."
- Chapter 8.3 Contact Charging p199, last paragraph on page: "Patents have recently been issued for other nonmagnetic insulating monocomponent development systems, ..."
- Chapter 9 Monocomponent Development pp204, see also Fig. 9.1: "One of the earliest monocomponent development systems that was used in a product was called aerosol or powder cloud development (references 9.1-7). Work on that system was first mentioned in the mid-1950s (references 9.1-3). ... ."
- Chapter 9.2 Early Work p208-211: "Work on monocomponent development was begun in the early 1950s at Batelle as part of the effort to find a viable development system for an automatic electrophoretic copier (reference 9.9). ... ."

Chapter 9.1 describes the aerosol or powder cloud development method that was early known to scientific community and reaches a very high resolution of toner deposition. This system uses a stream of air that removes all the particles that don't stick to the surface patterned with electrostatic charges, and it was used before 1988 in a commercially available copier:

- See also instant specification **[0034]** ... Substances which have not been mobilized or not linked can be washed from the support using a solvent, preferably a heated solvent, or mechanically removed from the support with the aid of a stream of air.
- Chapter 9.1 Aerosol or Powder Cloud Development p203, 2nd paragraph on page: "An obviously simpler development system is a monocomponent

system in which the only powder component is toner. That concept was, of course, well known to the early inventors of electrophotography. ... ."

- Chapter 9.1 Aerosol or Powder Cloud Development p205, last paragraph on page and Fig. 9.5: "As indicated above, this development system is in fact used commercially in the Xerox 125, an electrophotographic x-ray copier (Fig. 9.5).. ... ."

Chapters 9.2 and 9.4 describe a conductive monocomponent developing system:

- Chapter 9.2 Early Work, paragraph spanning pages 208-209: "The first conductive toner monocomponent development patent was issued to Gundlach (reference 9.13) of Xerox Corporation in 1965. The charging method is clearly induction, allowing a straightforward solution to the toner charging problem. ... ."
- Chapter 9.4 Conductive Toner, paragraph page 214: "The first monocomponent development system for an automatic copier was introduced in a product by 3M in 1971 (reference 9.22). It used magnetic, conductive toner that was charged inductively in the development zone."

In other words: the procedure to print toner particles in a spatially defined way is not critical for the particle-based combinatorial synthesis method; there is ample evidence that everybody educated in the field or even only tried to buy one or another kind of laser printer or laser copier knew by 1998 – and much earlier – that one- **or** two-component toners, with or without magnetic parts, and with numerous ways to charge the particles, could be used within a laser printer or laser copier. See also:

- Chapter 9.7 Summary, first paragraph page 223: "It has always been clear to electrophotographers that the monocomponent development system is simpler than two component, yet successful implementation was not achieved until 1980 with Canon's magnetic insulative development system."
- Chapter 9.7 Summary, first paragraph page 224: "Today, there appear to be two successful variants of the monocomponent development system

under development. Canon's, which uses magnetic insulating toner, and Ricoh's and Toshiba's, which use nonmagnetic insulating toner."

Yet another procedure is the liquid development:

- Chapter 10 Liquid Development, first paragraph page 225: "The most prevalent method of liquid development uses the phenomenon of electrophoresis. In electrophoretic development systems, charged particles, suspended in a nonconductive dielectric liquid, move in response to the electric fields of the latent image."

In addition to the numerous ways to transport the toner particles to the vicinity of our 2D surface patterned with electrostatic charges, numerous ways exist in addition to triboelectric charging to get these charges on the surface of a particle:

- Chapter 8.1 Induction Charging, pp187; see also Fig. 8.1: "Perhaps the easiest method of charging particles is to make them conductive, contact them to a metal and impose an electric field E_{air}. Charge will flow from the metal to the particle to exclude the electric field from the interior of the particle. . ...";
- Chapter 8.2 Injection Charging, pp192; see also Fig. 8.7: "The insulating toner is charged by injection from the roller in the presence of an electrical field (on page 192 first paragraph of Chapter 8.2). . ...";
- Chapter 8.4 Corona Charging, p200.
- Chapter 8.6 Other Charging Methods, pp200.

In summary, by the year 1988 a plethora of commercially available copiers and laser printers used a wide variety of different systems to charge and transport their toners. This data was freely available to the community, and even written in an easy to understand textbook.

Since nobody else before the instant patent application used solid particles to first transport chemicals, and then melt them and use them for a chemical reaction, we the claims to the combinatorial synthesis should be allowed.

In view of the above, each of the presently pending claims in this application is considered patentably differentiated over the prior art of record and

believed to be in immediate conditions for allowance. Reconsideration and allowance of the present application are thus respectfully requested.

Should the Examiner consider necessary or desirable any formal changes anywhere in the specification, claims and/or drawing, then it is respectfully requested that such changes be made by Examiner's Amendment, if the Examiner feels this would facilitate passage of the case to issuance. If the Examiner feels that it might be helpful in advancing this case by calling the undersigned, applicant would greatly appreciate such a telephone interview.

Respectfully submitted,

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Dedicated to my wife

CONNIE SCHEIN

Electrophotography (also called xerography), the technology inside the familiar copier, has become increasingly important to modern society. Since the first automatic electrophotographic copiers were introduced in 1959, they have become indispensable to the modern office and now constitute a multi-billion dollar industry involving many of the world's largest corporations. By the 1990s, it is expected that electrophotography will be one of the most prevalent printer technologies. This will occur because of the growing need for printers that are quiet, that can produce multiple fonts, and that can print graphics and images. Electrophotographic printers satisfy these requirements and have demonstrated economic and technical viability over an enormous speed range, from 6 to 220 pages per minute, with output quality that approaches offset printing.

Organizations contemplating designing a new electrophotographic copier or printer need to deal with two sets of issues. First, for each of the six process steps in electrophotography there are several different technologies that must be evaluated and chosen. For example, there are three development technologies (dual component, monocomponent and liquid); cleaning can be done with a blade or brush; and the photoconductor can be inorganic or organic, either of which can be configured in the form of a belt or a drum. Second, once a technology for each step is chosen, it must be optimized and integrated with the other process steps. This optimization and integration is facilitated by a firm scientific understanding of the technologies being considered. Unfortunately, certain key technologies in electrophotography are not well understood, even after years of industrial practice.

Perhaps the most crucial technologies which are not well understood are those used in the development step, because this step most directly determines the quality of the images. It is in this step that the "blackness" of the lines and solid areas, the cleanliness of the nonimaged areas, the uniformity of solid areas, and the ratio of the "blackness" of lines to solid areas are determined. Those who used Xerox copiers during the 1960s will remember that they would only reproduce the edges of solid areas (Fig. 3.1), a copy quality defect attributable to characteristics of the open cascade development system (Chap. 5). The generally perceived high copy quality of the Eastman Kodak line of copiers introduced in 1976 resulted directly from the introduction of a new development system, conductive magnetic brush development (Chap. 7).

Symbol	Unit	Description
A_c	cm^2	surface area of carrier
A_t	cm^2	surface area of toner
C_t	%	toner concentration: ratio of the mass of all toner particles on carrier to carrier mass
C_{AB}	C/V	capacitance between bodies A and B
C_0	C/V	capacitance between two bodies at 10Å separation
d_s	cm	photoreceptor thickness
d_t	cm	thickness of deposited toner layer
D		optical reflection density
e	1.6×10^{-19} C	charge on electron
E	eV	energy of a trap below conduction or above valence band
E_{air}	V/cm	electric field in air gap
E_{av}	V/cm	average electric field in air gap
E_D	V/cm	average electric field in developer
E_F	eV	Fermi level in metal
E_ℓ	V/cm	electric field in liquid (Chap. 10)
E_n	eV	neutral level of insulator
E_p	V/cm	electric field in photoreceptor
E_{th}	V/cm	threshold electric field
f		distribution function of either Q/r_2 or r
$\widetilde{F}$		fraction of toner removed from carrier bead
F	g/cm s	developer flow rate
F_{es}	dyne	electrostatic adhesion force
F_M	dyne	magnetic adhesion force
F_p	dyne	adhesion force of toner to photoreceptor

ρ_T	cm^{-3}	number of trapped charges per unit volume
σ	C/cm^2	toner conductivity (in liquid)
σ_c	C/cm^2	carrier charge per unit
σ_i	$(\Omega cm)^{-1}$	ionic conductivity (Chap. 10)
σ_p	C/cm^2	charge per unit area on photoreceptor
σ_s	$(\Omega cm)^{-1}$	charge per unit area
σ_t	C/cm^2	toner charge per unit area
σ_{tr}	C/cm^2	charge per unit area on the back of paper during transfer
τ	s	release time of a charge carrier from a trap
τ_l	s	time constant for liquid development
ϕ_i	eV	work function
ϕ_I	eV	insulator work function
ϕ_M	eV	metal work function
	newton	10^5 dynes, CV/m

1. Introduction

Electrophotography is the technology used in virtually all copiers commercially available today and it promises to be the most prevalent printer technology of the 1990s. This book has been written to assist both the newcomer and those already in the field to better understand this important and complicated technology and its most crucial subsystem, development.

Chapters 1 and 2 are tutorials written to assist the readers who may be new to electrophotography. The primary subject of the book, development physics, begins in Chap. 3 where all available development technologies are listed and compared. In the following chapters, the current state of our technical understanding is reviewed critically for each of these, along with their associated charging mechanism. Two component development systems are discussed in Chaps. 4–7; work on monocomponent systems is reviewed in Chaps. 8 and 9; and liquid development systems are described in Chap. 10.

In this chapter electrophotography is introduced with a discussion of its technical history and the current and projected markets. The evolution of the subsystems are traced from Carlson's first concepts in 1937 to present-day embodiments. The market for electrophotography really began with the introduction of the first automatic copier by the Haloid (now Xerox) Corporation in 1959. Since then the copier business has evolved into a multi-billion dollar revenue industry with many of the world's largest corporations participating. In addition, the already large electrophotographic printer business is expected to grow even faster in the coming decade as the demand for computer output devices continues to increase.

The only potential non-impact competitors to electrophotographic printing are two related powder marking technologies, magnetography and ionography. In magnetography, magnetic forces replace the electrostatic forces used in electrophotography. In ionography, the latent image is created by placing ions on a dielectric surface, eliminating the need for a photoreceptor. These two technologies and other variants of electrophotography also will be described in this chapter.

Technical details of the physics of electrophotography are reserved for Chap. 2. However, a basic knowledge of the process steps of electrophotography will make this chapter more readable. In Fig. 1.1 the six steps of the electrophotographic process are indicated schematically:

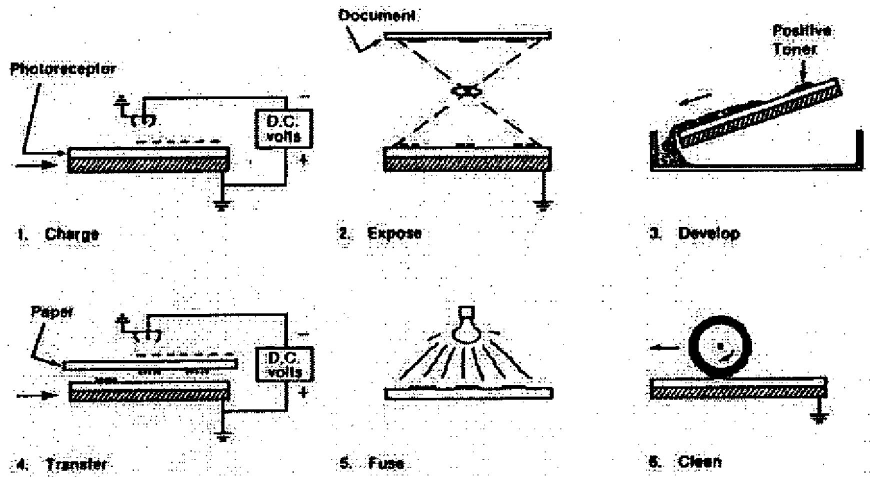

Fig. 1.1. Schematic diagram of the six steps of the electrophotographic process: charge, expose, develop, transfer, fuse and clean

Charge. A corona discharge caused by air breakdown uniformly charges the surface of the photoreceptor, which, in the absence of light, is an insulator.

Expose. Light, reflected from the image (in a copier) or produced by a laser (in a printer), discharges the normally insulating photoreceptor producing a latent image – a charge pattern on the photoreceptor that mirrors the information to be transformed into the real image.

Develop. Electrostatically charged and pigmented polymer particles called toner, $\approx 10\ \mu m$ in diameter, are brought into the vicinity of the latent image. By virtue of the electric field created by the charges on the photoreceptor, the toner adheres to the latent image, transforming it into a real image.

Transfer. The developed toner on the photoreceptor is transferred to paper by corona charging the back of the paper with a charge opposite to that of the toner particles.

Fuse. The image is permanently fixed to the paper by melting the toner into the paper surface.

Clean. The photoconductor is discharged and cleaned of any excess toner using coronas, lamps, brushes and/or scraper blades.

1.1 Technical History

Electrophotography [1.1–4] was clearly the invention of one man, *Chester Carlson* [1.5]. He conceived the need for a simple, inexpensive device that would allow office employees to copy any type of document. His background, a B.S. degree in physics and work in the patent offices of Bell Laboratories and P. R. Mallory Company, gave him extensive knowledge of patents related to copying processes.

During the 1930s, when Carlson was searching for a simple copying device, essentially the only copying method available was the Photostat process based on silver halide photography. Turn-around times could be several days, the "copy machine" was only available at a few service centers or county court houses, and the copies produced were reversed (because the customer was given a paper negative) with white letters on a black background. The diazo process (which requires ammonia fumes to develop the blue illuminated diazonium compounds coated on paper) and the earlier blue print process (which produced white lines on blue background by UV exposing iron salts coated on paper) remained engineering copying techniques. Others besides Carlson recognized the need for a better copying process and several alternatives evolved during the 1940s, including Eastman Kodak's Verifax process, a wet process also based on silver halide photography; 3M's Thermofax process, in which a special paper is developed by heat produced by the absorption of light in the printing on the document; and Gevaert's and Agfa's diffusion transfer process, a forerunner of the Polaroid process (without the pod) in which the unexposed silver salts in the positive image on film are caused to diffuse to another sheet of paper where they are reduced with special chemicals forming a positive image.

The two ideas that Carlson brought together in 1937 were: (1) the formation of an electrostatic latent image using photoconductivity to selectively discharge a surface charged insulator, and (2) "development" of this latent image by dusting with powders charged electrostatically. This joining of photoconductivity and electrostatics was a remarkable feat. Electrostatic charging of materials was, and in fact still is, a little understood, highly empirical, mostly ignored aspect of solid state physics. Photoconductivity of insulators was basically an unstudied science at the time of Carlson's invention.

It is clear from *Carlson's* writings [1.2] that he was familiar with prior experiments and patents in which electrostatic images were developed with charged powders. For example, he traced the history of charged powder development from Lichtenberg to Selenyi. In 1777 *Lichtenberg* [1.6] observed starlike patterns on insulators when dust settled onto a cake of resin that had been sparked. In 1936 *Selenyi* [1.7] demonstrated an electrographic recording system in which a charged pattern is written on an insulator (Fig. 1.2) by

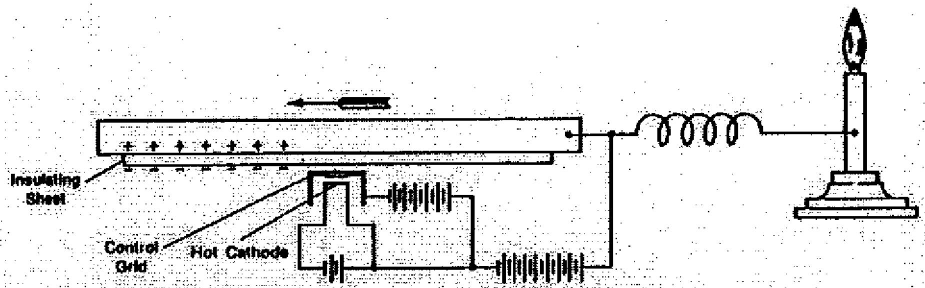

Fig. 1.2. Selenyi's electrographic recording system. A charged pattern is written on an insulator by controlling a cathode current to the insulator surface with a grid. A screw arrangement permits motion of the insulator surface in a spiral path for scanning the full page. By dusting with an insulating powder, the image is developed. The candle is used to erase the latent image [1.7]

controlling a cathode current to the insulator surface with a grid. By dusting with an insulating powder, the image is developed.

It is less obvious how Carlson came upon the idea of using thin photoconductive insulators to form a latent image. Quoting *Carlson* [1.2],

> The difficulties involved with the electrochemical systems led Chester F. Carlson to the conclusion that their relatively high current requirements were incompatible with the small currents available from photoconductive effects. Considering the photoconductor as an energy control element it became apparent to Carlson that the energy controlled by the system could be increased by greatly raising the voltage. This was difficult with electrochemical systems. A brief description of Selenyi's work on the powder development of electrostatic images formed by facsimile scanning appeared in the United States in 1936. Following this lead, Carlson began investigations of electrostatic image formation on photoconductive insulating layers which led him to the invention of electrostatic electrophotography the following year.

By 1937 Carlson had conceived of the process he called electrophotography. It was given a practical form with the help of Otto Kornei in October 1938, filed for patent in April 1939, and issued a patent in 1942 [1.5].

The first photoreceptors were composed of pure sulfur which had been fused and spread onto a metal plate and allowed to harden. Later, plates of sublimed anthracene layers with higher (!) light sensitivity were used. (To give the reader an idea of the sensitivities involved, "clean" anthracene used in experiments today has quantum efficiencies of $\simeq 10^{-4}$ as compared with unity for most modern photoreceptors; Carlson's anthracene was at best 10^4 times less sensitive than currently used photoreceptors.) The photoreceptor was charged "by rubbing it vigorously with a soft material such as a cotton or silk handkerchief." An alternative method was to place a transparent conductive plate parallel to the photoreceptor. When a voltage was applied between the back of the photoreceptor and the transparent conductive plate in the presence of illumination, the top surface of the photoreceptor became charged if the light and then the voltage were removed. Exposure of the photoreceptor to create the latent image was done, for example, by securing the plate to the back of a camera, where the image of the original was focused on the photoreceptor. Development to create a real image was accomplished by sprinkling a fine dust or powder from a can having a cloth or fine wire screen closing its mouth. Pulverized resins were preferred (because of fusing requirements) but gum copal, gum sandarac, ordinary rosin, sealing wax, dyed lycopodium powder, talcum powder, carbon dust, etc., were also used. The dusted plate was then subjected to a "...gentle draft of air by blowing the breath on it or directing air from the nozzle of a suitable blower against the dusted surface to blow off all loose powder not held on the surface by electrostatic attraction." Transfer of the powder to paper was accomplished by carefully laying the paper on the photoreceptor carrying the dusted image and firmly pressing against the surface by a block carrying a felt or sponge rubber pad. To improve the transfer, an adhesive such as plain water, wax or other soft or sticky sub-

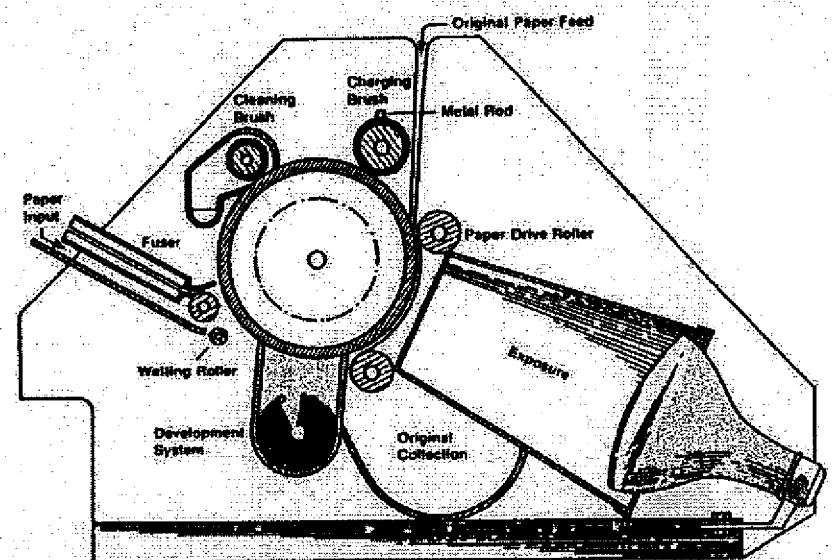

Fig. 1.3. The first automatic copy machine, invented by Chester Carlson [1.8]. In operation, the photoreceptor, coated onto a drum, is rotated first past a charging brush made of a plush-covered roller with a metal rod to drain off any electrical charge. The original is fed into a vertical slot and is driven in contact with the photoreceptor in front of the light source. It is then separated from the drum and deposited in the collection space. The development system consists of floating powder particles created by agitation of a brush; those opposite in sign to the latent image are attracted to it. A blank sheet of paper is fed in from the 9 o'clock position against a wetting roller (to promote transfer) and then against the photoreceptor. The fuser is two hot plates. Brush cleaning is suggested

stances could be applied to the paper. The preferred method of fixing was to melt the resin or wax powder into the paper.

Carlson worked alone until 1944, further developing the process and patenting [1.8] the first automatic copying machine (Fig. 1.3). Beginning in 1940 he tried to enlist commercial support for the invention, unsuccessfully approaching twenty well-known companies including RCA, Remington Rand, GE, Eastman Kodak and IBM. Finally in 1944 Carlson entered into a royalty-sharing agreement with Battelle Memorial Institute and joint development of the process began under Roland Schaffert. A short time later John Dessauer, the director of research at a little company in Rochester, New York, called Haloid (which was barely competing with Eastman Kodak and the Photostat Corporation in the photographic paper supply business for photography and Photostat copying), showed Joe Wilson, Haloid's president, an article on Carlson's electrophotography in *Radio News*. Wilson and Dessauer decided to gamble the company on the new copying technology and signed an agreement with Battelle in 1946. Haloid's funds, plus funds from the U.S. Army with interest in military photographic applications, accelerated progress in developing the technology. The process was first publicly announced and demonstrated by Battelle and Haloid at the annual meeting of the Optical Society of America in Detroit in October 1948. At that time the term xerography, meaning "dry writing," was coined from the Greek.

During the ten years after Battelle became involved, many basic inventions were conceived which made automatic copying a reality. For example, Bixby discovered that amorphous selenium layers prepared by vacuum evaporation onto aluminum were photoconductive insulators with much higher light sensitivity than sulfur or anthracene. Such selenium patents made it very difficult for competitors until other photoreceptors were invented. A corona wire charging device also was invented at Battelle, replacing Carlson's rubbing techniques. Walkup invented the screen controlled corona unit, which greatly lessened the danger of damage to the photoreceptor by overcharging. Walkup and Wise invented cascade development. In this development system, two powders, toner and much larger sized carrier, were mixed together. By carefully choosing the surface material of the carrier and toner, most of the toner would be charged with one sign (i.e. either all positive or all negative) and would electrostatically adhere to the carrier. The carrier with its attached toner would then be literally cascaded over the latent image, depositing toner in the process. Schaffert invented the electrostatic transfer method in which the back of plain paper was corona charged, electrostatically attracting toner in the process. These inventions formed the heart of the first automatic copier introduced by Haloid (Xerox) in 1959, the Model 914. The 914 was so named because it could reproduce documents up to 9 by 14 inches in size. It made seven copies a minute (cpm) and produced a revolution in the office. It is difficult to imagine an office today without a copier.

During those early years, the top priority had to be to produce a marketable product. Much of the information obtained was highly empirical and not suited for reporting in scientific journals. Status reports on the state of the technology appeared in 1965 in the form of two books, one by *Roland Schaffert* [1.1] entitled *Electrophotography* and one edited by *John Dessauer* and *Harold Clark* [1.9] called *Xerography and Related Processes*. These books demonstrate two interesting aspects of the technology: First, small groups of people (sometimes called "electrophotographers") were emerging with physical intuition about which parameters were important in each subsystem. Second, it was very difficult for people to accept that this complicated process was the best way to copy documents. Extensive searches for alternative, simpler and less expensive methods were (and continue to be) actively pursued, obviously so far unsuccessfully. Those who think they have new ideas for simplifying the process would be well-advised to read these books or the summary listed in Sect. 1.4; the early pioneers were very thorough.

In one sense the 914 copier failed to meet Carlson's vision: it was not an inexpensive device. This problem was solved by a marketing decision: copiers were not sold; instead, customers paid for each copy. That brilliant marketing decision brought the price of copying down to an affordable level for the typical office environment.

The corporations primarily involved in electrophotographic research during the 1950s and 1960s were Xerox, Eastman Kodak, IBM and RCA [1.3]. For Xerox, there was the obvious need to improve the technology. Slowly, more scientific approaches were applied to subsystem work. Eastman Kodak was motivated by the concern that electrophotography was a potential threat to its Verifax copying process and perhaps even to silver halide photography. Apparently, work was begun in the mid 1950s at Eastman Kodak, although the size of the effort has not been made public. Eastman Kodak had a variety of engineering models working during the 1960s, but it was not until 1976 that a product was actually introduced into the market. Part of the delay was due apparently to the fact that a simple, low cost natural follow-on to the Verifax process was not found. IBM's interest in electrophotography came, in part, from the desire to have faster computer printers, and IBM was licensed by Xerox for such applications. IBM also began work in the 1950s and early 1960s; some of the earliest work on novel monocomponent development systems and organic photoreceptors was begun during this period. RCA evolved an alternative copying process called Electrofax, in which the photoreceptor was built into the top layer of paper, eliminating the need for the transfer and cleaning steps and avoiding the selenium patents. This was the coated paper copying process in which photoconductive materials such as ZnO mixed in a binder was thinly coated onto paper. Copiers based on Electrofax were introduced by the Charles Bruning Company (Copytron 1000, the first machine to use magnetic brush development, which produced enlargements from microfilm), American Photocopy Equipment Corporation (Apeco Electrostat

copier, in 1961, the first office copier), SCM Corporation (Model 33 using liquid development), and the Dennison Manufacturing Company and Savin Corporation (Dennison Copier and the Savin Sahara copier, in 1964, which both used liquid development). However, customer preference for plain paper slowly eroded the coated paper copying market.

During the 1960s Xerox expanded its product line, introducing the 2400 series of copiers (40–60 cpm). Speed limitations and the inability of cascade development to reproduce solid areas brought about work on new development systems, including electroded cascade (used in the 2400 series) and later the magnetic brush development systems, invented during the late 1950s at RCA. IBM introduced its first copiers in 1970. The second model, introduced in 1972, used the magnetic brush development system. IBM was the first to use an organic photoreceptor coated onto aluminized Mylar in place of amorphous selenium. Being much softer, it had a substantially shorter life. To overcome this problem, the photoreceptor was made in the form of a long belt which was unrolled slowly from the inside of a drum; now the (rolled up) organic photoreceptor belt had an overall longer life than an amorphous selenium drum.

By 1975, IBM was able to introduce its first computer printer based on electrophotography, the model 3800. It runs at 215 prints per minute (ppm), and is still one of the fastest electrophotographic engines available commercially. The technology inside an electrophotographic printer is virtually identical to a copier with the exception of the exposure system. In place of lamps whose light is reflected from a document to the photoreceptor, a laser beam is scanned across the photoreceptor surface in a printer. The laser chosen by IBM was a HeNe laser. An acousto-optic modulator was used to turn the laser beam on and off corresponding to each picture element. The scanning of the laser beam was accomplished by reflecting it from the mirror facets of a spinning polygon spaced approximately 1 m from the photoreceptor. The technical problem which required invention in order to be solved was maintaining the laser position from line to line. To maintain line scan accuracy of, say, 25% for 10 lines per millimeter, requires 25 μm placement accuracy. At 1 m throw distance, a facet-to-facet angular accuracy of the polygon of 2.5×10^{-5} radians is required (equivalent to a pointing accuracy of 2.5 cm at 1 km distance)! The solution involved a clever optical trick, focusing the laser to a line on the facet face.

In 1975 an amazing coincidence occurred. Both Xerox and IBM upper management decided to discontinue their research efforts on electrophotography in their research divisions, at least partially because it was thought that electrophotography was a "mature" technology. At Xerox the majority of the electrophotographers from Research were transferred to the product development organization. Remaining applied research was directed to alternative copying and printing technologies including ink jet, magnetography, thermal printing, etc. At IBM, the primary basic research effort had been in photoreceptor development; the work was regarded as successful and transferred. The engineering solution of unrolling an organic belt solved the life problem. The sensitivity of the photoreceptor is close to the theoretical maximum. What more needed to be done? These decisions were later recognized as mistakes for several reasons. First, it opened up the technology to innovation by competitors. Second, no new technology was being developed for future machines. Third, research experts, who could be called upon to assist with problems in products being engineered, were no longer available. Fourth, future technology development had to be done in parallel with current product development, an extremely inefficient process. Fifth, rebuilding a research effort in electrophotography is a long term effort, with on-the-job training, aimed at learning the details of one subsystem and an overview of all the subsystems, taking several years.

Within one year, Eastman Kodak introduced its Model 150 copier. It was immediately recognized by the public and electrophotographers as a major advance in copy quality. The copier made the blacks blacker and the background cleaner. This was done by introducing a new development system: conductive magnetic brush development. The copier used an organic photoreceptor belt and the first recirculating automatic document feeder, which produced complete copies of reports ready for stapling by recirculating the originals each time a copy of the document was required.

Meanwhile, at Xerox during the late 1970s work was proceeding on the next mid-range copier, the 1075. The copy quality of the new Eastman Kodak copiers obviously had to be matched. As electrophotographic research was no longer being carried out in the research organization, the Xerox engineering team working on the 1075 had to shoulder the responsibility of both evaluating and bringing this technology into the new copier, no doubt contributing to the delays associated with the engineering of this product. It was finally introduced in 1982. With the 1075, Xerox introduced its first organic photoreceptor and a new charging device, the dicorotron, in which the corona wire is glass enclosed and subjected to a biased ac voltage, making it more resistant to contamination-induced nonuniformities.

By the late 1970s it was becoming increasingly clear that semiconductor lasers, which had significant advantages over gas lasers since they could be packaged in transistor-size containers and could be modulated by simply controlling the current, were going to have adequate power and life to be used in laser printers. Unfortunately their output wavelength is in the infrared, near 800 nm, where commercially available photoreceptors had little sensitivity. The search for an infrared sensitive photoreceptor was initiated at all major electrophotographic companies. At IBM, interest in using semiconductor lasers re-initiated the involvement of research in electrophotography.

A significant negative development also occurred in the late 1970s. Only three printing technologies could potentially challenge the speed and quality of laser-electrophotography: continuous ink jet, ionography, and magneto-

graphy. During the late 1970s, it became increasingly clear from work throughout the world that these alternatives would not replace laser-electrophotographic printing. To date only a few multiple nozzle continuous ink jet printers are marketed; ionographic printers are manufactured by one company, Delphax; and only one company, Bull Peripheriques, continues work on magnetography. This information, coupled with the rapidly increasing need for non-impact printers as output devices to the many computer systems becoming available, significantly heightened the potential commercial importance of the electrophotographic technology. (A fourth printing technology, bubblejet, a new form of ink jets, emerged during the early 1980s from the laboratories of Canon and Hewlett-Packard, also having the capacity to challenge electrophotography.)

Major developments in the technology came from Japan [1.3] during the period 1970–1980. Japanese companies, relying on their manufacturing strength, introduced low speed, low cost copiers, a segment of the market ignored by Xerox because it was felt that it was not possible to reduce the cost of the technology enough to make a viable product in this low speed and low volume range. The most successful during this time was Ricoh Corporation, which introduced copiers using a liquid development system (which were sold in the United States by Savin). Liquid development eliminated the need for a fuser, one of the most energy-intensive parts of the dry toner electrophotographic process; it also allowed the design of a smaller box requiring one-third of the number of components used in dry toner copiers, thus significantly improving reliability. These copiers were very successful, taking a significant share of the low end of the market.

Canon also made significant new discoveries. First, to avoid the selenium patents, Canon developed a new photoreceptor. It consisted of two layers, an upper insulating layer and a bottom photosensitive layer made from cadmium sulfide. A latent image was produced by simultaneously exposing and charging, causing the charge of the latent image to reside at the interface between the two layers. This was called by Canon the "New Process" (NP) and it forced the coining of a new name, "Carlson Xerography," for the usual latent image formation process. Canon began marketing NP machines in 1970 after eight years of development. These copiers also had liquid development. Second, in 1980, Canon announced the first copier with a monocomponent development system using insulative magnetic toner, the NP-200, a 20 cpm desktop copier. This system eliminated the carrier used in the cascade and magnetic brush development systems. Instead, magnetic material was put inside the toner, allowing magnetic forces to transport the toner into the development zone. There the toner developed across a gap in response to the dc electric fields of the latent image and a superimposed ac field. The development characteristics were excellent (good blacks, low background), the dry toner allowed the use of true plain paper, and the small size allowed the design of a small, relatively inexpensive tabletop copier. Within two years, Canon produced a whole line of copiers based on this monocomponent development system, from 12 to 30 cpm. The next big advance also came from Canon and addressed the Achilles' heel of electrophotography: reliability. In 1983 Canon introduced the cartridge concept for personal copiers. Many of the less reliable electrophotographic steps, including charging, monocomponent development, and cleaning, were incorporated into a throwaway cartridge in the PC-10 copier (8 cpm), which sold for the incredibly low price of $995 (plus $65 for the disposable cartridge, good for about 2000 copies). This copier was so inexpensive and the perceived reliability (actually availability) was so significantly increased that it opened up new markets in the low end of the copier business. Canon introduced yet another advance in 1985: the first amorphous silicon photoreceptor, which was put into its NP-7000 (50 cpm). The hardness of amorphous silicon is expected to significantly extend the life of the photoreceptors: 10^6 copies per drum and higher have been reported; 0.5×10^6 is guaranteed by Canon.

In 1982, Siemens introduced a new fuser, one based on chemical vapors, in its ND-3 printer. While vapor fusing was used on hand-operated copying equipment made by Xerox (Haloid) during the 1950s, this was the first time it was introduced in a high speed machine, 103 ppm. The challenge is to contain the organic vapors. This was achieved by bringing the roll paper after fusing into a refrigerated area that lowered the vapor pressure, condensing and capturing most of the organic solvent.

In the years 1984, 1985, several companies demonstrated that the laser-spinning polygon system used to convert a copier into a printer can be replaced with an all-solid-state device. Epson and Casio devised printers that use an array of liquid crystal shutters to address the photoreceptor. Behind the 10 liquid crystal shutters per millimeter is a uniform light source. In front is a Selfoc lens array which images the liquid crystals on the photoreceptor with a spacing of ≈ 1 cm. The Epson printer made 7 cpm; Casio's, 9 cpm. Neither is generally available to the public. Oki Electric Co. and NEC demonstrated printers with LED (light emitting diode) arrays. The Oki printer has a resolution of 10 dots/mm and a speed of 10 or 20 ppm; the NEC printer has a resolution of 12 dots/mm and a speed of 8 ppm. Two new LED printers were introduced by IBM (12 ppm, 12 dots/mm) and Eastman Kodak (92 ppm, 12 dots/mm). These "image bar" technologies present solutions to two manufacturing challenges: the maintenance of sufficient light uniformity among the elements and with time (as the elements degrade) and the interconnection of all of the elements to driver electronics at a reasonable cost (so it can compete with the laser-polygon system).

Another contribution, again from Japanese companies, was announced at the 1985 IEEE-IAS (Industrial Application Society) annual meeting in Toronto. Both Ricoh and Toshiba recognized the potential benefits of monocomponent development with nonmagnetic toner, such as lower toner manufacturing cost and the potential for better colors than could be obtained

Table 1.1. Commercially available copiers $\left(\frac{\text{Model}}{\text{Development technology}^{a}}\right)$

Copies/ min.	Xerox	Kodak	IBM	Canon	Ricoh	Oce	Konica (Royal)
120	9900 DI						
90	1090 DC	250 DC					
70	1075 DC	150, 225 DC	Series III DI	NP 8070 MIM			
60	3600 DI					1825 MCM	
							5503 DI
50	1050 DI			NP 7050, 500 MIM	FT 6085 DI		5003 DI
	5400, 5600 DI					1725 MCM	
40	2400 DI			NP 4540 MIM			4003 DI
	1040 DI			NP 4035 MIM	FT 5070 DI		
30					FT 5000 DI		
							2803 DI
				NP 270, 3525 MIM			
	3400 DI			NP 3025 MIM			
	1038 DI						
	1025 DI				FT 4065 DI		
20							
							1803 DI
				NP 150 MIM	FT 2050 MIM		
							1503 DI
	1012 DI						1200 DI
	1020 DI			NP 115 MIM			
10					RiPRO MIM		
8				PC10, 20, 30 MIM	RIPRO-jr. MIM (black) MIN (color)		
6				PC3, 5 MIM			

Table 1.1 (cont.) Commercially available copiers $\left(\frac{\text{Model}}{\text{Development technology}^{a}}\right)$

Copies/ min.	Sharp	Toshiba	Sanyo	Panasonic	Minolta	Mita	Savin (Ricoh)
120							
90							
70							
60	SF 9600 DI						
50	SF 9500 DI					DC-513Z DI	7050 L
				FP-4520 DI	EP 650Z DIμ		
40							
					EP 550Z DIμ		
							7040, 7350 L
	SF 9300 DI		Z 122 DI				
	SF 8600 DI						
30		BD 7816 DI		FP 3030 DI	EP 470Z DIμ	DC-313Z DI	870, 5030 L
				FP 2625 DI	EP 450Z DIμ		
					EP 410Z DIμ		
		BD 5610 DI				DC-213RE DI	
20	SF 8100 DI						
			Z 116 DI				
						DC-152Z DI	
				FP 1530 DI	EP 350Z DIμ		
		BD 4121 DI					
	SF 7200 DI		SFT 70 DI	FP 1300 DI			
						DC-1001, 111 DI	
10	SF 7100 DI	BD-3110 DI			EP 50 DIμ		
8	Z-50 DI		SFT 600 DI				
6							

[a] D: DUAL; I Insulating; C Conducting; μ: Micro-carrier. M: MONOCOMPONENT; I Insulating; C Conducting; M Magnetic; N Nonmagnetic. L: LIQUID

with toner loaded with magnetic material. They simultaneously announced nonmagnetic monocomponent development systems; so far only Ricoh has manufactured products with this system.

It would seem, with the observed rate of new ideas, that Chester Carlson's electrophotography after 50 years still has a way to go before "maturing." Who could have ever guessed in the early days that such a complicated process would even work, let alone be the dominant copying and printing technology in the last two decades of this century?

1.2 Copier Market

The number of copiers and their features and speeds has grown enormously in the 29 years since Xerox introduced the 914 copier. Listed in Table 1.1 are most of the commercially available copiers from companies that manufacture them, along with their development technology. Clearly a large choice is available to the consumer. Plotting a table such as this as a function of time shows that Japanese copiers are dominant in the low end and are slowly challenging the high speed market dominated today by Xerox, Eastman Kodak, and IBM.

Under the model number is listed the development technology. The first letter (D, M, L) distinguishes between dual or two component (magnetic brush), monocomponent and liquid; subsequent letters define which variant is used, as discussed in succeeding chapters. A study of this table reveals that most copiers use insulative magnetic brush development (Chap. 6); only Eastman Kodak and Xerox use conductive magnetic brush development (Chap. 7). Monocomponent development systems are used by Canon, Ricoh, and Océ. Canon uses magnetic, insulating; Océ, magnetic, conducting; and Ricoh, both magnetic and nonmagnetic, insulating (Chap. 9) systems. Only Savin (in the United States) sells copiers using liquid development systems, which are manufactured by Ricoh.

The reason for the large number of commercially available copiers is the huge market, 14 billion dollars in the United States in 1986. The 1986 market and estimates of the 1991 U.S. market by segment are shown in Table 1.2 taken from information provided by Dataquest [1.10]. They divide the market into seven segments.

Segment PC (personal copier) includes copiers that have speeds up to 12 cpm, have moving platens, sell for an average of $1100 and make about 400 copies per month. These types of copiers are easy to install, have minimal features, superior reliability, and are compact and lightweight. An example is the Canon PC-5. This is predicted to be the fastest growing segment of the market, going from $294M in 1986 to $600M in 1991, or a 15.3% CAGR (compound annual growth rate).

Table 1.2. U.S. copier market (Dataquest, September 1987) [1.10]

Segment definition			Market[a]		
	Speed [cpm]	Average retail price [$]	1986 [Millions of U.S. dollars]	1991	Compound annual growth rate [%]
PC	up to 12	1100	294	600	15.3
1	up to 20	2500	2320	2170	−1.3
2	21−30	4700	3030	2840	−1.2
3	31−44	7400	2440	3230	5.8
4	45−69	11400	2000	3820	13.9
5	70−90	16000−73000	2020	1710	−2.3
6	91+	78300−129775	1890	1910	0.2
Total			13994	16280	3.1

[a] Includes hardware, service and supplies

Segment 1 includes tabletop copiers up to 20 cpm, with an average monthly volume of 3500, and an average price of $2500. These copiers have some features such as reduction or enlargement, optional input/output devices, and 11 × 17 inches maximum copy size. An example is the Minolta EP-350Z. This market segment is expected to shrink from $2320M to $2170M, a CAGR of −1.3% over the period 1986−1991.

Segment 2 copiers have speeds of 21−30 cpm, make 7200 per month, and sell for $4700 on the average. They have features similar to those in Segment 1. An example is the Toshiba BD-7816. This market segment is also expected to shrink from $3030M to $2840M, a CAGR of −1.2% over the same period.

Segment 3 category copiers are increasingly offered as systems with standard features of reduction/enlargement, feeders and sorter. They typically have speeds of 31−44 cpm, make 14000 copies per month, and sell for an average price of $7400. An example is the Sharp SF-9300. The market will grow by 5.8%, from $2440M to $3230M.

Segment 4 copiers are highly featured machines such as the Ricoh FT-6085. They typically have a speed of 45−69 cpm, make 24000 copies per month, and sell for an average price of $11400. This segment has the second highest predicted CAGR of 13.9%, from $2000M in 1986 to $3820M in 1991.

Segment 5 includes highly featured, fast copiers such as the Ektaprint 225, Xerox 1075, and IBM Series III. They typically have a speed of 70−90 cpm, have a monthly volume of 63000 copies, and sell for $16000 − $75000. They feature modular options including finishing, input/output options and magnification. The segment is expected to shrink by 2.3% from $2020M to $1710M by 1991.

Segment 6 includes the fastest copiers such as the Xerox 9900 and the Ektaprint 250. They sell in the range $78000 − $130000, have a speed of

Table 1.3. Price per copy

Segment	Speed [cpm]	Copies/month [thousands]	Purchase price	Price per copy [¢/copy]					Total price
				Purchase price	Maintenance	Supplies			
						Cartridge	Toner	Developer	
PC	up to 12	1.5	$ 1145 $95 cartridge/2000 copies	1.27	0	4.75			6.02
2	21–30	8	$ 5000	1.04	2.72		0.29	0.13	4.18
3	31–44	20	$ 9500	0.79	1.41		0.21	0.09	2.50
5	70–90	60	$ 30000	0.83	0.88		0.11	Included in maintenance	1.82
6	91+	300	$ 130000	0.72	0.66		0.08	0.04	1.50

Assumptions: Five-year amortization, no financing, supplies for one year purchased, fuser oil ignored (small), paper price not included. Numbers are only representative of published values

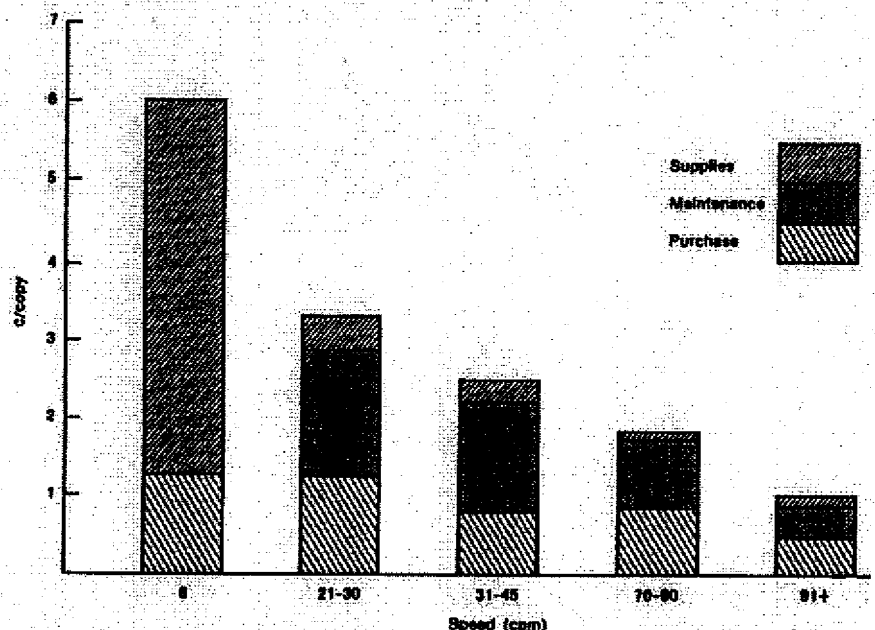

Fig. 1.4. The price a customer pays per copy for typical machines in several of the market segments. The price per copy goes up as the speed goes down, from 1.5¢ at 91+ cpm to 6.02¢ for the slowest copier (see Table 1.3)

91+ cpm, and make an average of 210 000 copies per month. This segment is expected to grow slightly, 0.2%. Its revenue in 1986 was $1890M.

The total copier market is anticipated to grow from $14 000M to $16 000M, or a CAGR of 3.1% from 1986 to 1991.

It is of interest to calculate the price the customer pays per copy across the speed range. The assumptions and numbers are shown in Table 1.3 and the data are plotted in Fig. 1.4. The purchase price has been amortized over five years and typical published prices of maintenance and supplies have been used. As can be seen, the price per copy (excluding paper) dramatically increases as the speed decreases, from 1.5¢/copy for the highest speed copiers to 6.02¢/copy for the slowest copiers. Most of the price per copy for the slowest speed copiers is due to the high cost of the replaceable cartridge, the invention that led to the increased reliability (actually availability) of these copiers. Among Segments 2–6, the increasing price per copy as speed is reduced is due primarily to the increasing price of maintenance.

1.3 Printer Market

The need for printers, which are primarily output devices for computers, has grown with the computer industry. The recent enormous proliferation of computers, availability of document preparation software, and large-scale access to data bases have led to a rapidly expanding electrophotographic printer business. This is because printers based on electrophotography are quiet, can handle multiple fonts, and can produce pictorial information over a wide speed range. Reliability concerns (relative to impact printing technologies) are being addressed by innovative manufacturing and engineering approaches. For example, some printers allow customers to throw away used-up parts, such as the Canon customer replacement cartridge concept. Others use internal microprocessors to diagnose and aid customers in fixing their own machines. Still others even use these microprocessors to call, by themselves, a central office requesting service and specifying parts required.

In 1973, Xerox introduced the first modern electrophotographic printer, the Xerox 1200, which was based on the Xerox 2400–3600 series of copiers. The copier optics were replaced by spinning character masks in front of xenon flash lamps. Each mask with all the characters for a font set spun in front of xenon flash lamps at each character location across a line. Obviously, font flexibility was limited to the character set on the spinning mask. By 1975, 1976, IBM and Canon had introduced the first laser-based electrophotographic printers, the IBM 3800, operating at 215 ppm, and the Canon LBP 2000 C1 operating at 31 ppm. Both used HeNe gas lasers. By 1977, many more products had appeared, including the Xerox 9700 (based on the 9200 copier) operating at 120 ppm, the Hitachi 8196–20 operating at 112 ppm, the

Siemens ND-2 operating at 206 ppm, and the NEC 7370 operating at 112 ppm. A significant product, announced in 1983, that opened up the low speed, low cost market was the Canon LBP-CX, an 8 ppm printer, built by adding a semiconductor laser to its PC-10 low cost copier.

At present there are a large number of manufacturers offering electrophotographic printers. A list of the major manufacturers is given in Table 1.4. Other corporations offering such printers include Hitachi, Fujitsu, NEC, Burroughs, Hewlett-Packard, Minolta, Sharp, and Eastman Kodak.

The reason many corporations are manufacturing electrophotographic printers is the expected market growth. U.S. market forecasts provided by

Table 1.4. Some commercially available printers $\left(\frac{\text{Model}}{\text{Development Technology}^a}\right)$

Prints/min.	Xerox	IBM	Siemens	Canon	Ricoh
220		3800 DI			
			ND-2 DI		
120	9700 DI	3800-6 DI			
			ND-3 DI		
70	8700 DI				
50	4050 DC 5700 DI			LBP-3400 MIM	
40					LP-4400 DI
30		6670 DI			
	3700 DI				
20		3820 DIμ		LBP-20 MIM	
					LP-3150 MIM
12	2700 DI	3812 DI			LP-4120 MIM
10	4045 DI			LBP-CX MIM	
8				LBP-CX MIM	LP-4080 MIM
6					PC-6000 MIN

[a] D: DUAL; I Insulating; C Conducting; μ: Micro-carrier. M: MONOCOMPONENT; I Insulating; C Conducting; M Magnetic; N Nonmagnetic. L: LIQUID

Table 1.5. U.S. printer market (Dataquest, August 1987) [after 1.11]

Segment definition		Market[a]		
	Speed [ppm]	1986 [Millions of U.S. dollars]	1991	Compound annual growth rate [%]
1	up to 10	1220	4630	30.6
2	11–20	379	2800	49.2
3	21–30	106	578	40.3
4	31–50	387	950	19.7
5	51–80	432	640	8.2
6	81–150	583	845	7.7
7	151+	1220	1200	−0.3
Total		4325	11643	21.9

[a] Includes hardware, service and supplies

Dataquest [1.11] are shown in Table 1.5: the overall market is expected to experience a compound annual growth rate of 21.9% from \$4300M in 1986 to \$12 000M in 1991. Very similar printer market predictions have been made by CAP International [1.12]. Dataquest divides the printer market into seven segments.

Segment 1 covers printers with speeds up to 10 ppm and includes the Hewlett-Packard Laserjet and the Apple Laserwriter, both built on the Canon LBP-CX engine. This segment is predicted to grow by 30.6% per year from \$1220M to \$4630M from 1986 to 1991.

Segment 2 has the largest predicted CAGR, 49.2%. These printers have a speed range of 11–20 ppm. Examples include the IBM 3812 and the Texas Instruments 2015. The market is expected to grow from \$379M to \$2800M from 1986 to 1991.

Segment 3 has the second largest predicted growth rate: 40.3%. Printers in this segment make 21–30 ppm. An example is the Xerox 3700. Here the market is predicted to grow from \$106M to \$578M.

Segment 4 printers can print at speeds of 31–50 ppm, and include the Xerox 4050 and the Ricoh LP4400. This segment is expected to grow at a CAGR of 19.7%, from \$387M to \$950M.

Segment 5 printers have speeds of 51–80 ppm. The market is expected to grow from \$432M in 1986 to \$640M in 1991, a CAGR of 8.2%. Examples are the Xerox 4060 and 8700.

Segment 6 printers have speeds of 81–150 ppm. Examples include the Xerox 9700, Siemens 2200, and the IBM 3800-6. The market is predicted to grow modestly, by 7.7%, from \$583M to \$845M.

Segment 7 is presently the largest market, \$1200M, but is anticipated to shrink slightly by 1991 with CAGR of −0.3%. Examples include the Siemens 2300 and IBM 3800-3.

3. The Development Step

Mastery of the development step in the electrophotographic process is challenging for three reasons: (1) this step usually determines the best image quality the copier or printer will produce, (2) significant aspects of the physics of development are not well understood, and (3) as a result, significant empirical material and hardware parameter searches are standard procedure in optimizing a development system for a new copier. Reducing the "black magic" of the development system should result in a better, more efficiently optimized system. Therefore the focus of the reminder of this book is on a thorough description of our current, but limited, understanding of the physics of the development process. We describe and compare known development systems in this chapter. Detailed discussions of the physics occurring in each development system and their associated toner charging mechanism are the subjects of succeeding chapters.

3.1 Challenges

The copy quality challenge results from the fact that the development step determines the best image quality a copier produces. The blackness of line copy and the blackness and smoothness of solid areas are determined by the amount and uniformity of toner developed onto the latent image. The whiteness of the nonimaged areas (the background) is determined by the amount of toner developed onto the nonimage areas of the photoreceptor. A casual glance by the reader will reveal that almost all copies made by electrophotography have a light gray appearance in the nonimage areas caused by unwanted toner. Comparison with offset print quality (from a book or catalog) dramatically reveals the difference.

Two quantum leaps in copy quality have been the direct result of the introduction of new development systems. The cascade development system (Chap. 5) was used in the first automatic copier, the Xerox 914. Only the edges of solids were reproduced and background development was high by today's standards. A test pattern reproduced on a copier with a cascade de- →

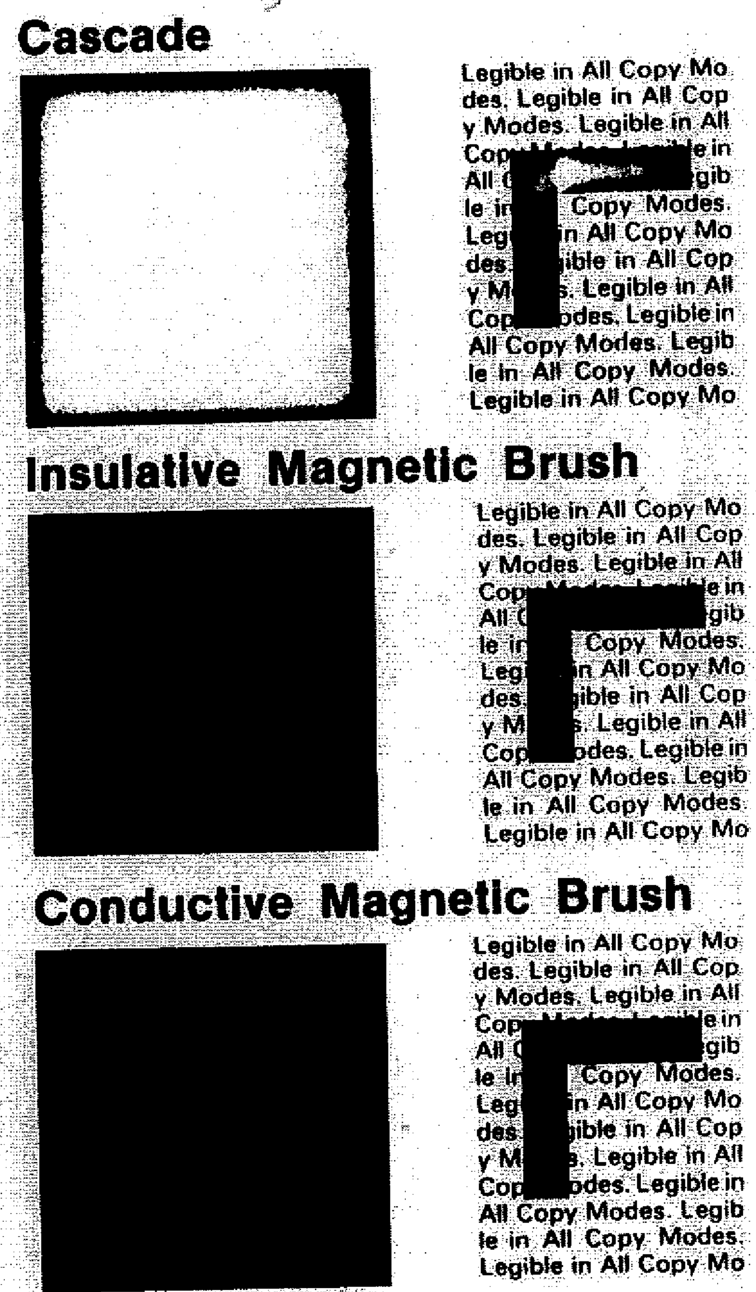

Fig. 3.1. A test pattern including solid area, typical characters and background reproduced on copiers using: (a) cascade development, (b) insulative magnetic brush development, (c) conductive magnetic brush development

velopment system is shown in Fig. 3.1a (the original test patterns look like Fig. 3.1c). The cascade development system was replaced with insulative magnetic brush development (Chap. 6) in the early 1970s primarily to improve this solid area development defect; it also improved background development and permitted higher copying speeds. Note that the solid areas (Fig. 3.1b), while filled, are less dense or uniform than the lines. In 1975, the conductive magnetic brush development system (Chap. 7) was introduced by Eastman Kodak. Note the enhanced blackness of lines and solids (Fig. 3.1c), the uniformity of the solids, and the equality of the blackness of lines and solids. In addition, background development was further decreased. The Eastman Kodak line of copiers was immediately perceived by the public and electrophotographers as a set of significantly improved products.

The scientific challenge results from the fact that significant aspects of the physics of development are not understood today. Two examples are background development and toner charging. Lists of background mechanisms are available (Sect. 6.6) but virtually no data or quantitative theory exist. Our understanding of toner charging, which is critical to solid area as well as line copy development and is probably critical to background development, is in the pre-scientific era, primarily based on empirical studies. Toner charging, specifically, and insulator charging, generally, remain one of the least-understood branches of solid state physics. Enormous disagreement exists among workers who study insulator charging (Sect. 4.2) and, consequently, guidelines for developing new toners are virtually absent. That a background theory should be possible is suggested by the status of our understanding of solid area development. Theories of solid area development are available (Sects. 6.3.4 and 7.3) which have been validated experimentally. As a result, the primary material and hardware parameters driving solid area development have been identified. This has resulted from carefully controlled experiments using special hardware with which reproducible, highly accurate data have been obtained. Solid areas are the obvious first aspect of development to study because the "simple" electric field makes both experiments and theory easier.

Our lack of knowledge of the physics of background development and toner charging creates the third technological challenge. Without hardware or material guidelines, mastery of the development step is very costly in terms of manpower and time because extensive empirical hardware and material searches are standard procedure in optimizing a development system for a new copier. With no predictive ability or off-line tests, one can only proceed by building actual hardware, making copies, and running lifetests. This is an expensive and wasteful manpower-intensive procedure. Even worse, after a failed life test, it is unclear whether to make a hardware or material change.

An example of the procedure followed in optimizing a new development system illustrates the point that our lack of knowledge is costly. It is known, i.e., in the electrophotographic folklore, that a tradeoff exists between line copy and background development. A lower average toner charge-to-mass ratio Q/M increases line copy development but also increases background development. The standard hardware approach (after trying to get the background specification raised!) is to set Q/M to achieve the background specification and then to change other variables, such as number of rollers in the magnetic brush development system (Sect. 2.1.3), to achieve the line copy specification. This can become expensive when the number of rollers approaches 3 or 4. It can also have a deleterious effect since mechanical stress is placed on the developer mix at each roller-photoreceptor gap, causing damage to the surface of the toner and carrier particles. This can lower Q/M, which increases the background! A better approach might be to try to understand the basic reason why a tradeoff seems to occur. Perhaps the reason lower Q/M causes increased background is that such mixtures have more wrong-sign toner. If this is the case, then narrowing the toner charge distribution should allow one to reduce simultaneously the average toner charge (increasing line copy development), and the amount of wrong-sign toner, minimizing background development. Such an approach requires knowledge of the physics determining the toner's charge distribution and physics of background and line copy development.

3.2 Focus

The primary focus of this book is a thorough description of our current understanding of the physics of the development process. This includes solid area, line copy, and background development for all known development systems and their associated toner charging mechanism. A secondary focus is to point out areas where significant unanswered questions exist to encourage future research.

That significant issues are associated with the physics of solid area development can be demonstrated with two simple calculations. First, if development proceeded until the toner charge per unit area σ_t completely neutralized the latent image (surface charge σ_p) then after development (Fig. 3.2)

$$\sigma_t = \sigma_p \,. \tag{3.1}$$

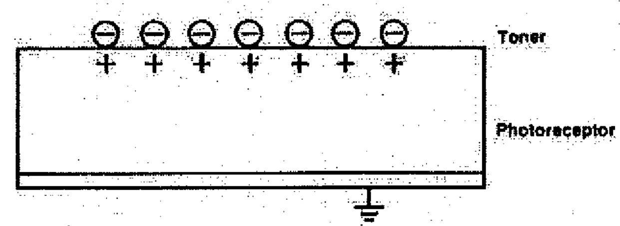

Fig. 3.2. The neutralization condition occurs when the toner charge per unit area equals the photoreceptor charge per unit area

Since

$$\sigma_t = \frac{M}{A}\frac{Q}{M} \tag{3.2}$$

and

$$V = \frac{\sigma_p d_s}{\varepsilon_0 K_s}, \tag{3.3}$$

where M/A is the developed toner's mass per unit area, Q/M is the developed toner's charge to mass ratio, V is the electrostatic potential associated with the charge of a solid area latent image a dielectric distance d_s/K_s from the ground plane, and ε_0 is the permittivity of free space, then neutralization predicts

$$\frac{M}{A} = \frac{V\varepsilon_0}{(Q/M)(d_s/K_s)}. \tag{3.4}$$

Such high M/A 's are never observed. For example, for a typical organic photoreceptor one can assume $d_s = 20\ \mu$m, $K_s = 3$ and $V = 600$ V. A single roll magnetic brush development system operating with toner having $Q/M = 20\ \mu C/g$ will produce approximately 0.45 mg/cm^2 (Sect. 6.4); (3.4) predicts 4.0 mg/cm^2, nine times higher than observed. Hence a factor other than neutralization limits development.

Second, only a small fraction of the toner available for development is used. At synchronous motion (the magnetic brush roller and photoconductor are moving at the same speed), the total amount of toner in the carrier chain per unit area of the carrier chain is

$$\frac{M}{A} = C_t \frac{M_c}{4R^2}\frac{L}{2R}, \tag{3.5}$$

where C_t is the toner concentration (ratio of toner to carrier mass), M_c is carrier mass, $4R^2$ is the area occupied by the carrier, L is the photoconductor to roller gap and $L/2R$ is the number of carrier beads per chain in the gap. Adding the speed ratio factor (v_r/v_p, roller divided by photoreceptor velocity) to account for nonsynchronous motion, we obtain (with ρ_c being the carrier density)

$$\frac{M}{A} = \frac{\pi}{6} C_t L \rho_c \frac{v_r}{v_p} \tag{3.6}$$

counting all the toner in the bead chains, or

$$\frac{M}{A} = \frac{\pi}{3} C_t R \rho_c \frac{v_r}{v_p} \tag{3.7}$$

counting only the toner in first layer of carrier beads [obtained by omitting the $L/2R$ factor in (3.5)]. This predicts (for $C_t = 2\%$, $L = 1250\ \mu$m, $\rho_c = 5$ g/cm^3, $v_r/v_p = 2$, $R = 100\ \mu$m) 13 mg/cm^2 total toner in the bead chains, or 2 mg/cm^2 toner in the first layer of carrier beads, again at least an order of magnitude more than is observed. Most of the toner passing by the latent image is unused.

Line copy development is actually much more important than solid area development from the point of view of usage. However, study of it has been limited for two reasons. First, it is obviously a more complicated problem because of the nonuniform electric fields. Second, it is observed that the ratio of line copy to solid area development is somewhat constant, 1.5–2, for insulative magnetic brush development and close to 1 for conductive magnetic brush development (consistent with the model discussed in Chap. 7).

The electric fields associated with lines have been studied [3.1–3] and a qualitative understanding is useful for grasping the complicated nature of this problem. *Neugebauer* [3.1] solved the electrostatic problem of a line of charges on a dielectric, i.e., photoreceptor surface. He showed that the electric field depends on the thickness of the dielectric and the width of the line, and varies rapidly in space above the line. Variations of the perpendicular field as a function of distance above a 25 μm thick dielectric with dielectric constant 6.6 charged to 100 V for a line of 10 μm half width are shown in Fig. 3.3.

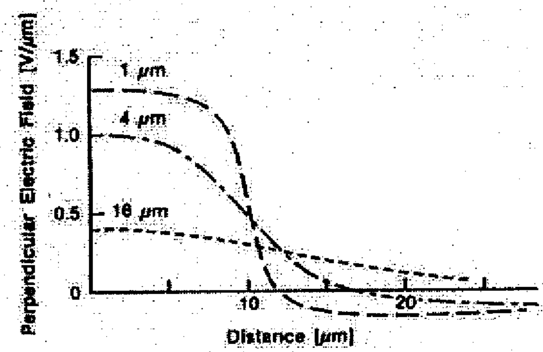

Fig. 3.3. Perpendicular electric field plotted versus the distance (1, 4, 16 μm) above a 25 μm thick photoreceptor of dielectric constant 6.6 for a line charge half width of 10 μm [3.1]

The sensitivity to line width is shown in Fig. 3.4. Note the rapid spatial variations of the electric field and that at large line width, i.e., solid areas, the electric field goes to zero. Now imagine adding to the space above the line moving 200 μm diameter metal balls (carrier beads) which must maintain an equal potential across their surfaces. This will obviously change the electric field both spatially and with time. Further, as toner develops and neutralizes some of the line charge, the electric field lines will move toward the interior of solids, and development will proceed toward central areas, increasing the thickness of fringe field development at the edge of solids. If that were not

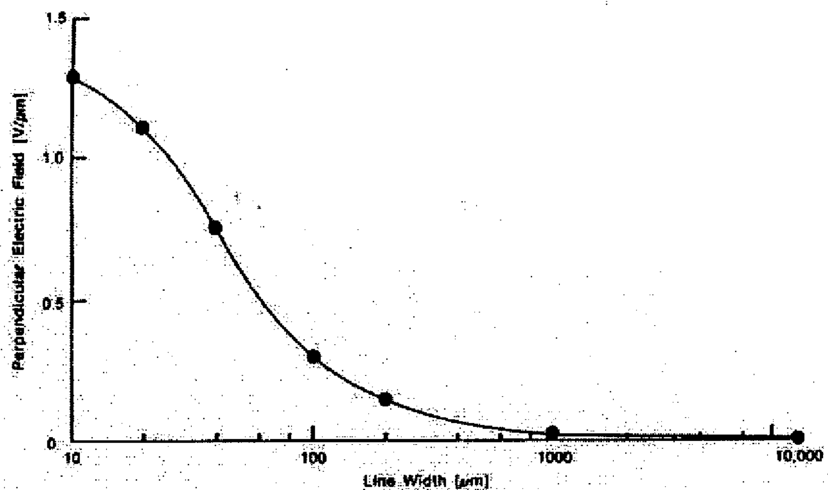

Fig. 3.4. Perpendicular electric field component at the center of a line charge plotted versus the width of line [3.1]

complicated enough, it is unclear where in space to evaluate the electric field when calculating toner development. Some workers have evaluated the field at a toner radius over the photoreceptor, but that is probably not accurate for either a powder cloud or a field stripping mechanism of development (Chaps. 5 and 6).

An estimate of the ratio of line to solid area development can be made by ignoring most of the problems mentioned above. If a counter electrode is added (Fig. 2.7), a uniform field is added to the above fringe field of

$$E_{air} = \frac{V}{d_s/K_s + L/K_E}\ , \qquad (3.8)$$

where V is the electrostatic potential of the latent image (3.3), L is the the distance between the photoreceptor and the counter electrode, and K_E is the dielectric constant of the developer mix. For $V = 100$V, $L = 1250$ μm, $K_E = 1$, this field is 0.08 V/μm, small compared to the fringe fields (Fig. 3.3). If $K_E = 7$ (approximate value for insulating magnetic brush development as shown in Sect. 6.2.2), this field becomes 0.55 V/μm, about half the fringe field value. These numbers suggest that the electric fields due to lines are approximately twice as strong as the electric fields due to solids, and 2:1 ratios of line to solid area toner mass per unit area are reasonable for insulating magnetic brush development.

The development mechanisms governing background development represent extremely important but essentially unexplored areas of development

physics. One may regard the development system as a signal-to-noise discriminator, where solid areas and lines are the signal and background is the noise. Pity the poor engineer who must maximize the signal-to-noise ratio, yet has little insight into the noise sources! Where information is available on background development, it will be mentioned. It is hoped that this book will encourage research on this problem.

There are other aspects of the development technologies which will not be discussed, such as the design and mechanism of particle flow in the dual component development systems, lifetime problems, and sensing and replenishment of toner.

3.3 Descriptions

One of the first problems faced by the inventors of electrophotography was devising methods of charging the toner particles and bringing them into close proximity with the photoreceptor containing the latent image; i.e., inventing a development system. A history of the various ideas tried can be found in the books by *Schaffert* [3.4] and *Dessauer* and *Clark* [3.5]. We will focus here on those development systems which have successfully made it into products.

Cascade development, invented [3.6] during the Haloid-Battelle collaboration and used on the first electrophotographic copiers is one of the dual component development systems, so named because both toner and carrier are used. The carrier in this system is polymer-coated glass beads with diameters of several hundred micrometers. Contact between the carrier and toner surfaces causes charge exchange (via static electricity, Chap. 4). This neutral mixture of charged toner and (equal and oppositely charged) carrier is literally cascaded down the photoreceptor surface (Fig. 3.5). Bead motion is con-

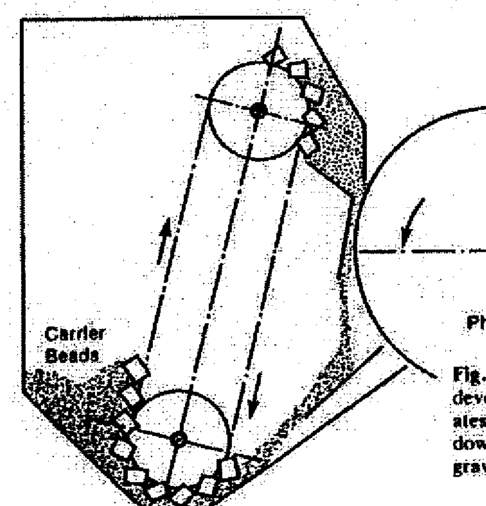

Fig. 3.5. A schematic diagram of cascade development. Cascade development operates by literally cascading carrier beads down the photoreceptor under the force of gravity [3.7]

trolled by gravity, imposing an architectural design constraint. The counter electrode, capacitively coupling the electric field out of the photoreceptor, is very far away (Fig. 2.7), leading to the classic solid area washout (Fig. 3.1) associated with these copiers. The carrier particles are recirculated while the toner is used up as it is developed onto the photoreceptor. Hence, means must be provided to sense depleted toner, add toner, and mix new toner with the carrier to produce the proper charge. These functions add considerable complexity to the system. Many of the ideas for possible mechanisms of development, such as the powder cloud and field stripping models, were conceived by researchers working on this system. A discussion of the results of this work can be found in Chap. 5.

Magnetic brush development, invented in the late 1950s at RCA [3.8], has completely replaced the cascade system today. It is used in almost all copiers with speeds above 30 cpm This is also a dual component system, with toner and carrier, but the carrier is made from magnetically soft material such as iron or ferrite. At the bottom of the roller (Fig. 3.6) the carrier is attracted to the stationary magnets and, by magnetic forces and the resulting friction forces, the carrier beads are transported around the rotating roller. Because magnetic forces are used, the architectural design constraint imposed by gravity in cascade development is removed. For enhanced development several rollers can be utilized. Usually the developer mix is magnetically passed from one roller to the next. Because magnetic material is usually conductive, the counter electrode is much closer to the latent image and solid area development is now possible. Quantifying the magnitude of the distance to the counter electrode, in a region of moving conductive balls, has been a challenging electrostatic problem, as discussed in Sect. 6.2.2. The physics associated with this development system has been the most studied of all development systems, and the discussion in Chap. 6 is correspondingly the most extensive.

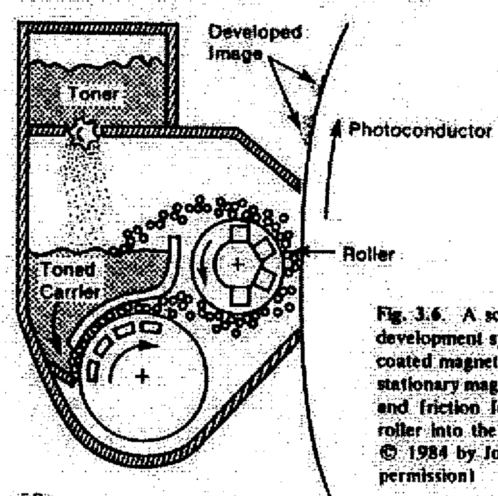

Fig. 3.6. A schematic diagram of a magnetic brush development system. The carrier, which is polymer-coated magnetically soft material, is attracted to the stationary magnets and, by a combination of magnetic and friction forces, is carried around the rotating roller into the development zone [3.2]. (Copyright © 1984 by John Wiley and Sons, Inc.; reprinted by permission)

In the mid-1970s Eastman Kodak [3.9] announced an improvement to the magnetic brush development system. They replaced the spherical carrier particles with irregularly shaped particles (called sponge carrier). To understand why this constituted an important advance, one must understand that toner development on the photoreceptor with insulative spherical carrier is limited by the buildup of charge on carrier beads adjacent to the photoreceptor (Chap. 6). The use of rough beads allows this charge to be short circuited to the roller, significantly increasing the amount of development possible (Chap. 7). The counter electrode now becomes so close, basically at the carrier adjacent to the photoreceptor, that lines and solids look the same electrically. The line to solid area electric field ratio, and consequently the line to solid mass-per-unit-area ratio, approaches one, the ideal situation, approaching the quality produced by offset printing.

All the development systems described so far are dual component, that is, they require two components, carrier plus toner. Having two components entails some nontrivial hardware complications, which involve the sensing of depleted toner and the addition and mixing of fresh toner. These complications can be avoided with a monocomponent development system in which only toner is used. Such systems have been researched over the years by almost all of the manufacturers of copiers. 3M and Canon Corporation were the first to introduce commercial versions of these systems.

There are three independent characteristics of monocomponent development systems: conducting or insulating toner, magnetic or nonmagnetic toner, and contact or noncontact between the photoconductor and the toner-loaded roller. Monocomponent development systems are used usually in low speed machines, below 20 cpm, where manufacturing cost is particularly important.

The first such system was introduced by 3M [3.10] in the early 1970s, the VHS (for very high speed) copier operating at 20 cpm. It used conducting toner, magnetic transport, and contact development. By loading the toner with magnetite, magnetic forces could be used to move the toner into the development zone (Fig. 3.7). In this system the magnets rotate and the roller is stationary. The high conductivity of the toner allowed the use of induction, an extremely simple method of charging. The field due to the latent image induced charge flow through the toner chain to the toner particles adjacent to the photoconductor, which were then attracted electrostatically to the latent image. Unfortunately this system has two inherent flaws (Sect. 9.4), monolayer development (hence, gray copy) and humidity sensitive transfer, which have caused it to be all but abandoned.

In the early 1980s Canon introduced another monocomponent development system [3.12] based on insulating toner, magnetic transport, and noncontact (they called it jumping) development (Sect. 9.5). The charging of the toner was achieved using static electrification (instead of induction), just as in dual component systems, with the other part of the tribo-couple being the roller surface (Fig. 3.8). Magnetic forces were again used for transport. In

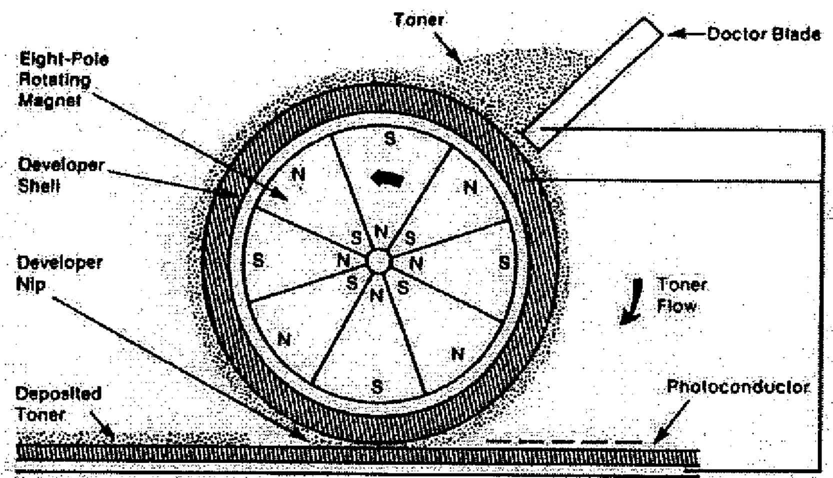

Fig. 3.7. In 3M's conductive monocomponent development system the magnets rotate inside a stationary shell, causing the toner chains to move in the opposite direction around the shell into the development zone [3.10,11] (© 1983 IEEE)

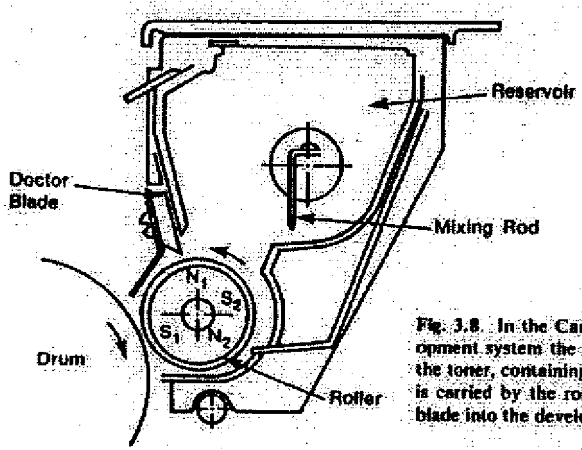

Fig. 3.8. In the Canon monocomponent development system the magnets are stationary and the toner, containing magnetically soft material, is carried by the roller past a magnetic doctor blade into the development zone [3.12]

order for the toner to jump across the gap, large (1200 V p-p) ac fields were superimposed across the development zone. This development system has been extremely successful for Canon and is used in their full range of products, from their personal copier PC10 to their higher speed versions NP-8070, covering a range from 8 to 70 cpm.

A nonmagnetic development system might also be attractive because of the potential lower cost of manufacturing toner and the ease of making colored toner. In 1985, Ricoh [3.13] and Toshiba [3.14] discussed such systems at the

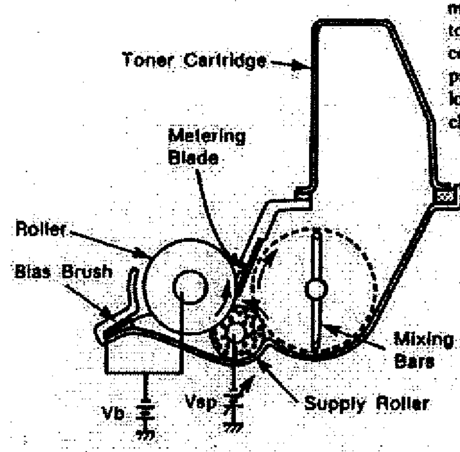

Fig. 3.9. In the Ricoh nonmagnetic monocomponent development system, the toner is brought into contact with a roller by contact with a soft supply roller; those toner particles which escape through a spring-loaded metering blade obtain a uniform charge and thickness [3.13] (© 1985 IEEE)

annual IEEE-IAS conference in Toronto. The Ricoh system (Fig. 3.9) uses contact development and has since appeared in products: a copier, the Ricoh RePRO jr. (8 cpm), and a printer, PC Laser 6000 (6 ppm). The Toshiba system uses noncontact jumping development. Both are discussed in Sect. 9.5. As shown in Fig. 3.9, in the Ricoh version the toner is still brought near to the photoconductor with a roller. The roller is loaded by flooding it via a supply roller with a bath of toner, which must escape through a spring-loaded metering blade. When it exits this region, it is of uniform thickness and charge. Clearly, sophisticated material engineering has been achieved.

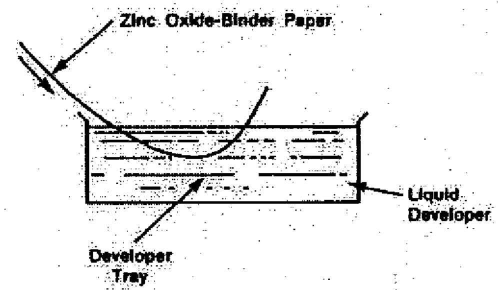

Fig. 3.10. A schematic of the immersion-type liquid development system [3.15]

All of the above systems use dry powder to develop the latent image. Liquid development systems [3.15] have also been used in copiers. Perhaps the most successful were copiers made by Ricoh, because they produced slow but small, inexpensive and reliable copiers, a market ignored by Xerox during the 1970s. In these systems (Fig. 3.10) the latent image is dipped into a liquid that contains charged toner particles. Obviously the liquid must be insulating so that it does not destroy the latent image. This requires the use of organic

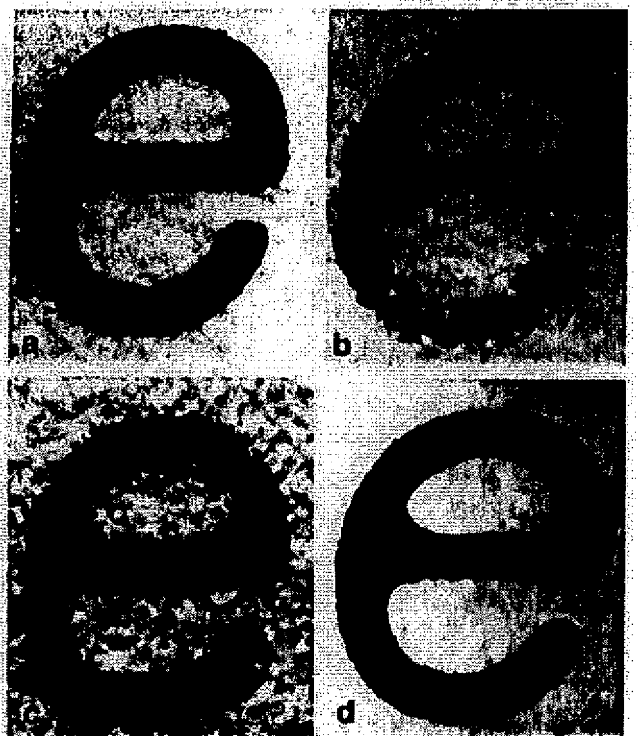

Fig. 3.11. A comparison of the print quality for (A) lithography, (B) liquid development, (C) dry toner electrophotography, and (D) a new form of liquid development called ElectroInk. Note the lack of edge crispness in the dry toner system as compared to the liquid toner systems [3.16]

solvents, a nontrivial concern. However, liquid development produces some of the highest quality images (Fig. 3.11) because it uses smaller toner particles, less than 1 μm, and because it usually develops close to neutralization. Eastman Kodak [3.17,18] recently announced a color proofing system based on a liquid-development electrophotographic process that operates at approximately one page every few minutes. A discussion of the liquid development system is found in Chap. 10.

4. Toner Charging for Two-Component Development Systems

In two component development systems, two powders, toner and carrier, are mixed together (Fig. 2.9). Toner particles have diameters of approximately 10 μm and are blends of polymers and carbon black pigment. Carrier particles have diameters of approximately 200 μm and are composed of magnetically soft cores coated with a thin polymer coating. Contact between the toner and carrier causes charge to be exchanged. Depending on the materials chosen for the toner and carrier coating, the resulting charge on the toner may be positive or negative. This mixture, which has zero net charge, is introduced into cascade or magnetic brush development systems, as described in Chap. 3, where toner particles are attracted to the latent image on the photoreceptor.

The proper charge properties of the toner are crucial requirements for a good development system. The average charge-to-mass Q/M ratio determines the amount of toner developed onto solid area and character latent images; the lower Q/M, the darker the images on the page. It is believed that wrong sign toner is "developed," i.e., attracted to photoconductor, onto nonimaged areas, giving an objectionable gray color to the white paper. Zero charged toner becomes dust in the machine, leading to reliability problems.

The phenomenon of charge exchange between contacting materials is a pervasive and interesting solid-state physics problem which remains poorly understood. It is pervasive in both a negative and positive sense. Sparks generated by static electricity may cause explosions in mines, flour mills and supertankers. One merely has to walk across a rug under low relative humidity conditions and experience the shock on touching grounded metal for a demonstration of the pervasiveness of charge exchange phenomena (between shoes and rugs). In the positive sense, besides electrophotography, electrostatic charge exchange is used in electrostatic precipitators to control pollution and in electrostatic spray painting.

It is an interesting phenomena because it occurs between all materials (metals and insulators, organic and inorganic) and remains one of the few solid-state physics problems that is at such a rudimentary level of understanding. The difficulties in making progress in this field should not be underestimated and are well documented in prior reviews and books [4.1–8]. When the surfaces of two materials are brought into contact and separated, the actual area which made contact is difficult to determine. Whether pure contact or friction is required has not been determined. In fact, the terms contact

Electrophotography and Development Physics is concerned with the increasingly important and complicated technology of electrophotography (also called xerography), familiar to most people in the form of photocopiers and laser printers. After a description of the physics of the complete electrophotographic process, this volume presents a critical review of the three types of development systems (dual component, monocomponent and liquid) and their associated toner charging mechanisms. On mastering this material, the reader will have a working knowledge of the electrophotographic process and a detailed knowledge of what is known and not known about its most important subsystem, development.

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time for the brush to move the electrode to the carrier beads adjacent to the photoreceptor is not known. However, the falloff appears at a similar frequency as was observed for insulative magnetic brush (Fig. 6.27), suggesting Scharfe's assumption is correct.

7.6 Background Development

No information on background development specific for conductive magnetic brush development systems has been published. Background development is generally observed to be less than that observed in insulative systems. This could be due to the larger reverse electric fields in the background regions.

7.7 Summary

Conductive magnetic brush development has produced significantly improved copy quality, both by producing increased M/A's for lines and solids, increasing the customer-perceived "blackness," and by making the optical reflection density of lines and solids equal.

Several theories have been proposed to account for this increased efficiency which can be characterized by the conductivity of the bead chain: infinite, partial, insulative. It appears that the theory proposed by Schein et al., which assumes infinite conductivity down the bead chain and field stripping of toner from the carrier beads adjacent to the photoreceptor, is consistent with all of the experiments. The theory quantitatively describes solid area development and explains why lines and solid areas have equal "blackness" or M/A. No data or theories of background development have been given for this development system.

8. Toner Charging for Monocomponent Development Systems

Just as in two component development systems, toner for monocomponent systems must be charged so that the electric field of the latent image can exert its Coulomb force. The problem which this chapter addresses is how to charge and transport toner when carrier is absent. The following chapter discusses the physics of the development process in which monocomponent toner is attracted to the photoreceptor.

Toner particles used in monocomponent development systems are similar to toner particles used in the two component systems (Sect. 4.4). They are polymer-based with carbon black added for colorant. Magnetic properties, if needed, are obtained by adding magnetite, γ-Fe_3O_4, or similar materials, with 50% loading not uncommon. Higher conductivity, when required, is obtained by adding additional carbon black to the bulk or surface. Triboelectric charging is enhanced by the addition of charge control agents. As for toner for two component development systems (Sect. 4.4.3), the patent literature is rapidly evolving.

Similar to the situation in two component development systems, the charge properties of the toner critically affect the performance of the development system. Wrong-sign toner can produce background, uncharged toner produces dust and the average charge-to-mass ratio determines character and solid area optical density. In addition, as in two component systems (Sects. 6.3.4, 7.3), the steepness of the M/A versus V curve, which partially determines the gray scale rendition, can also be affected by the charge properties (Chap. 9).

A surprisingly large variety of charging methods have been identified and incorporated into monocomponent development systems. Probably the simplest is induction charging of conductive toner, patented by 3M in the 1970s and currently being used in Océ copiers. Insulating toner can be charged by injection (3M) or contact electrification (Canon, Ricoh, Toshiba). Corona charging of insulating particles has been suggested (Xerox, IBM). Other methods of charging and transporting particles, not yet applied to the creation of new monocomponent development systems, also will be discussed.

8.1 Induction Charging

Perhaps the easiest method of charging particles is to make them conductive, contact them to a metal and impose an electric field E_{air}. Charge will flow from

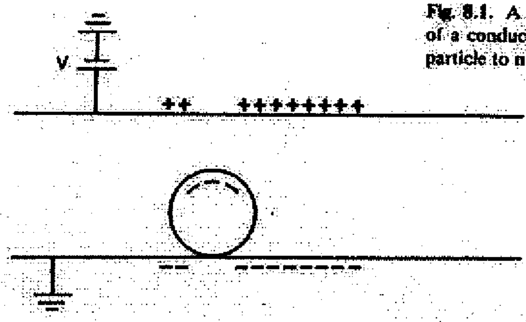


Fig. 8.1. A configur...n for induction charging of a conductive particle. Charge flows into the particle to null internal electric fields

the metal to the particle to exclude the electric field from the interior of the particle.

A configuration for single-particle induction charging is shown in Fig. 8.1. A conducting particle sitting on the negative plate becomes negatively charged. Due to electrostatic repulsion, it is repelled from the negative plate. It then lands on the positive plate, loses its negative charge and becomes positively charged. It is then repelled from the positive plate. The particle will bounce between the two plates. *Choi* [8.1] has shown that the average electric field at the surface of a spherical particle on the plate is 1.65 times the electric field of the charging plates. Hence, the induced charge Q and the charge-to-mass ratio Q/M are

$$Q = (1.65\,E_{air})(4\pi\varepsilon_0 r^2), \qquad (8.1)$$

$$Q/M = 4.95\varepsilon_0 E_{air}/r\rho_t, \qquad (8.2)$$

where r is the particle radius, ρ_t is the particle's density, and ε_0 is the permittivity of free space. By allowing the particles to escape from a small hole in one plate, Choi characterized the charge and radius of inductively charged conductive particles. Quantitative agreement with (8.1) was obtained (Fig. 8.2).

Making the particles conductive provides a charging method, but a development system still requires a means of transporting the particles. *Kotz* [8.2] suggested using magnetic forces. By loading the toner with magnetic material such as magnetite, he could move the toner around a roller, see Fig. 8.3. Either the magnets or the outside roller can rotate. When the magnets rotate the toner moves in the opposite direction because the motion is determined by the erection and falling of toner chains, following magnetic field lines. In the development zone the toner is chained by the radial magnetic field between the roller and the photoreceptor surface, forming a conductive path. In the presence of the electric field due to the latent image, charge flows down the toner chains, charging the toner particles at the ends of the chains adjacent to the

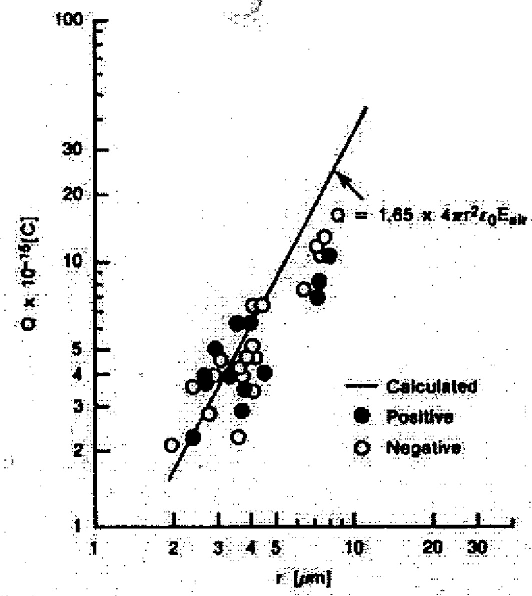


Fig. 8.2. Charge characteristics of carbonyl nickel particles charged inductively [8.1]

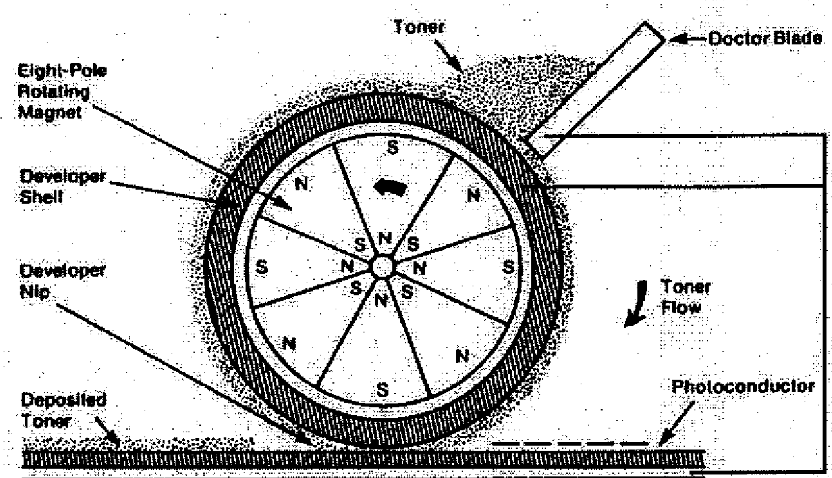


Fig. 8.3. Schematic of a development system that uses induction charging. The magnets rotate, causing the toner to move around the roller in the opposite direction. In the development zone, charge flows down the toner chains in response to the electric fields of the latent image [8.3] (© 1983 IEEE)

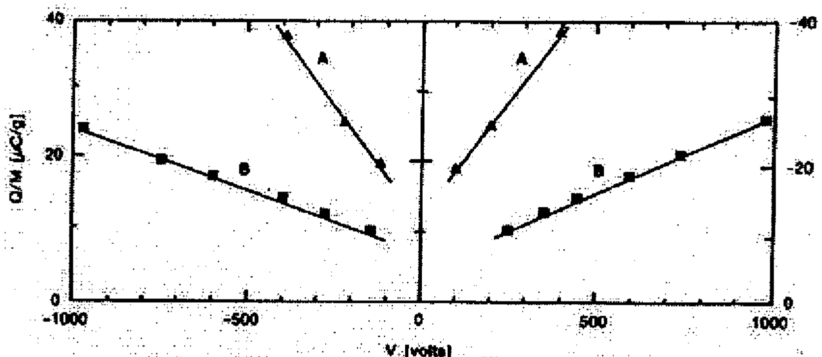


Fig. 8.4. Relationship between the magnitude of the developed toner's charge-to-mass ratio and surface potential of photoreceptor layer for two conductive toners. Note that Q/M is V shaped about zero volts, characteristic of conductive toner [8.4]

photoreceptor, which will then adhere to the latent image because of the Coulomb force.

Of course, either positive or negative charge can be induced on the toner. Hence a measurement of the magnitude of the developed toner's charge should be V shaped about zero volts. This has been shown by *Shimada* et al. [8.4] among others (Fig. 8.4). This result implies that reverse biasing to minimize background development (Sect. 2.1.3) is not possible with this system unless a diode characterization can be built into the toner. This may have been achieved by *Shimada* et al. [8.4].

Setting the resistivity of the toner requires careful consideration. Assuming a simple *RC* circuit charging model, the time constant for the charge to move down the chain is simply $\rho K_t \varepsilon_0$ where K_t is the dielectric constant of the toner, and ρ is the resistivity of the chain. Clearly this must be much smaller (say $10\times$) than the time the toner is in the development zone (20 ms for a nip width of 1 cm and a roller velocity of 5 cm/s). This implies that the resistivity should be much less than 10^{11} Ωcm. Characterization of the effective toner chain resistivity is not simple because it obviously includes interfaces between toners. Further, the resistivity of such particulate systems is often electric field dependent, as shown by *Faust* [8.5] (Fig. 8.5). *Katz* [8.2] argues that too low a resistivity may cause the toner charge to leak onto the photoreceptor surface, effectively destroying the latent image, and suggests a preferable toner is "highly conductive under developing field conditions when electrical current flow is desirable to create imaging forces and less conductive prior to and after development when the electric fields are substantially reduced and current flow is not desired." Another consideration: a resistivity intermediate in value, such that $\rho K_t E_0$ is approximately equal to the development time, could lead to very erratic results because ρ can easily vary from chain to chain.

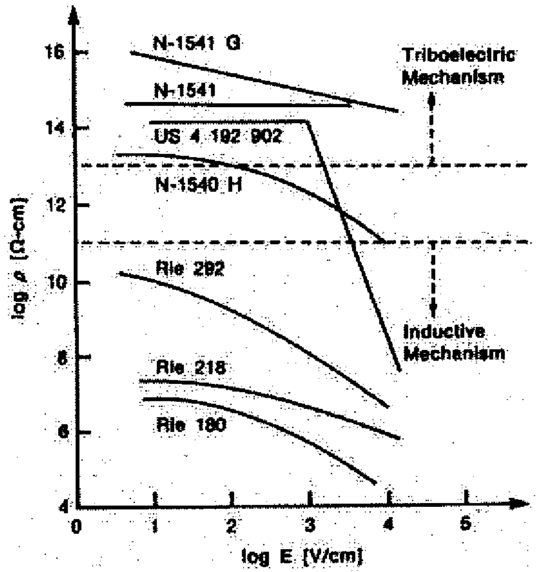


Fig. 8.5. Volume resistivity versus electric field for different mono-component magnetic toners [8.5]

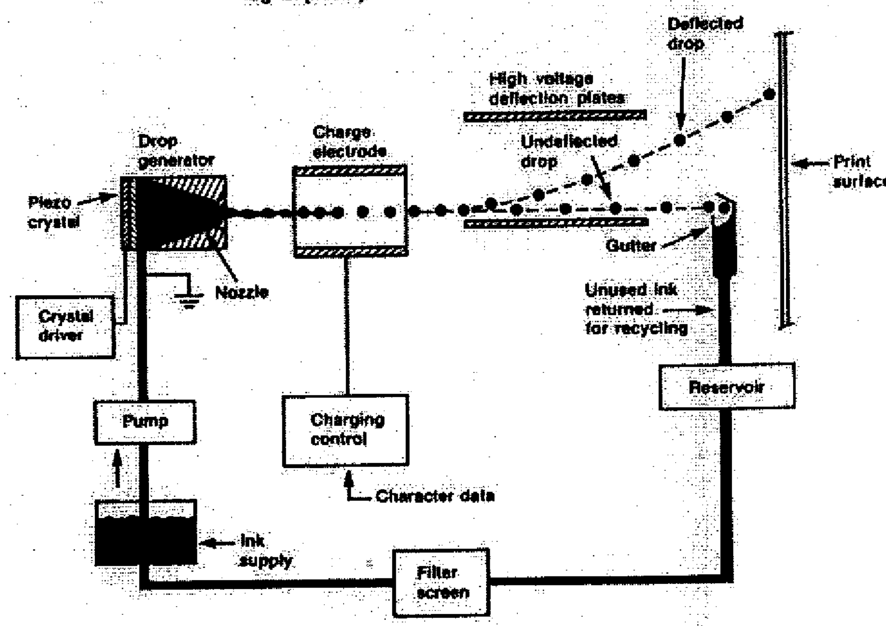


Fig. 8.6. One form of ink jet printing uses conductive ink which is inductively charged and then deflected with an electric field [8.6]. (Copyright 1977 by International Business Machines Corporation; reprinted with permission)

Development problems (Sect. 9.1) with this system caused by the high conductivity of the toner have led people to consider methods of charging insulating toner.

As an aside, this induction method of charging is used in another nonimpact printing technology, continuous ink jet printing (Fig. 8.6). As a stream of conductive ink breaks into drops, induced charge is trapped on each drop. A Coulomb force caused by an applied electric field acting on the charged drop is used to deflect the drop to the proper position on the paper.

8.2 Injection Charging

Injection charging methods as shown in Fig. 8.7 were also patented by 3M [8.7]. In this case insulating magnetic toner is metered to a thickness of approximately 250 μm (or about 25 toner layers) on a roller surface. Toner is transported around the roller by rotation of either the roller or the magnets. The insulating toner is charged by injection from the roller in the presence of an electric field. A critical aspect of this invention is the provision of a means to produce rapid, turbulent physical mixing of the toner particles so that uniform charging occurs.

The details of precisely how the turbulence contributes to toner charging remain unclear. That dynamic effects associated with the roller velocity are important is well documented by all groups working on this problem. If the photoreceptor is replaced with a metal plate and the current flowing in an applied field from the roller to the metal plate is measured, it is found to be

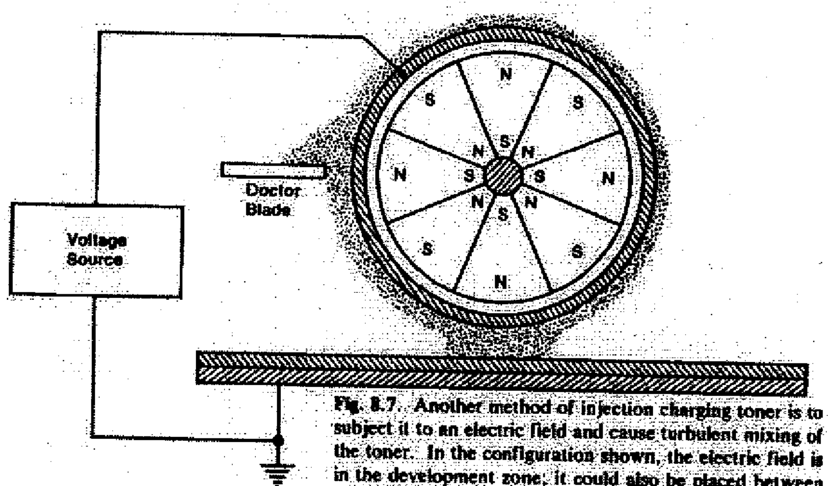


Fig. 8.7. Another method of injection charging toner is to subject it to an electric field and cause turbulent mixing of the toner. In the configuration shown, the electric field is in the development zone; it could also be placed between the doctor blade and the roller [8.7]

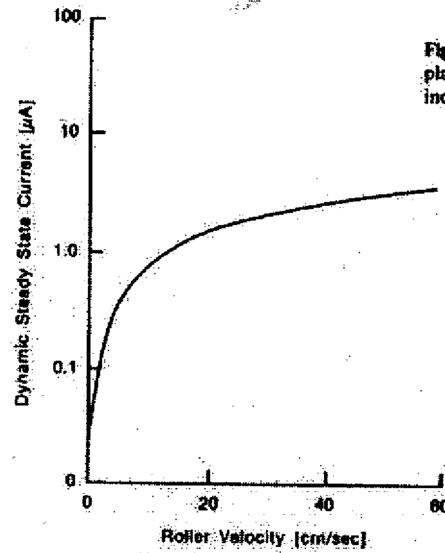


Fig. 8.8. Current between the roller and a metal plate placed in the position of the photoreceptor increases strongly with roller velocity [8.7]

strongly dependent on roller speed. Figure 8.8, which shows this effect, is taken from *Nelson*'s patent [8.7]. The same result has also been reported by *Field* [8.3], *Nakajima* et al. [8.8], and *Lee*, *Imaino* et al. [8.9–13]. Nelson suggests that the charge injected into a toner particle can be later transferred from one toner to another in the presence of an electric field. Nakajima et al. provide an interesting picture that depends upon chain rotation (Fig. 8.9).

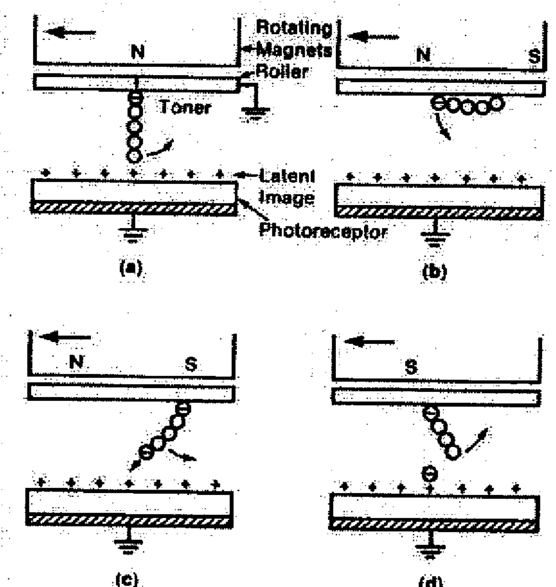


Fig. 8.9. A model for toner charging of high-resistivity toner by injection from the roller [8.8]

Field argues that rapid toner movement is possible in the charging region. He postulates that charge injection occurs at the electrode-toner interface and then charged toner rapidly moves to the vicinity of the photoreceptor in response to the electric fields.

A study of the complications involved in this process was presented by *Lee* and *Imaino* and co-workers in a series of papers [8.9–13]. They showed that different current characteristics and presumably toner charging characteristics can be obtained by varying R_{dd}, defined as the ratio of the development gap to the doctor gap. At values of R_{dd} less than 0.9, i.e. high packing fraction, their toner behaved conductively, producing a dc current when exposed to an applied bias, with a metal plate substituted for the photoreceptor. At values of R_{dd} above 0.9, the dc current progressively decreased, i.e., the interparticle conductivity decreased, and they observed a transition to a simple exponential current-time relationship. They associated this with mass transport of the charged toner particles. These current-time curves also produced evidence for toner development. During the first revolution of the roller, the current was observed to decrease relatively rapidly, which was associated with toner development onto the electrode. This was observed at large values of R_{dd} which Nelson recommended for optimum development conditions. This work was coupled with direct observations of the toner flow through a transparent plastic window. Only at large R_{dd} is toner development observed. At smaller ratios, individual particles are not fixed with respect to their neighbors and the velocity near the electrode, i.e. the plastic window, is much smaller than that near the roller surface. When the roller rotates with the magnetic field fixed, toner filaments form larger lumps, or trees, that cartwheel along the surface. This is probably the source of the kinetically enhanced conductivity. An unexpected observation is that the trees sit on a static layer. The conductivity region occurs when the toner in this layer is sheared and interparticle interactions occur. This occurs at a value of R_{dd} of about 0.8. They concluded that charge is injected at the metal contact and currents (and charging of the bulk toner) result from mass transport and interparticle contact. Ultrasonic measurements which probe interparticle forces and magnetic force calculations which partially determine these forces were also carried out on this system [8.12, 13].

8.3 Contact Charging

Triboelectric or contact charging has become the most important monocomponent charging method. It is used by Canon [8.14] in their line of copiers, from the PC 10 (8 cpm) to the NP500 (50 cpm), and by Ricoh [8.15–17] in their new copier, the RePRO jr. Toshiba [8.18] and Xerox [8.19] have papers and patents using this charging method. Undoubtedly, its growing importance is due to the efficient toner charging made possible by the use of charge control agents which make the toner more triboelectrically active.

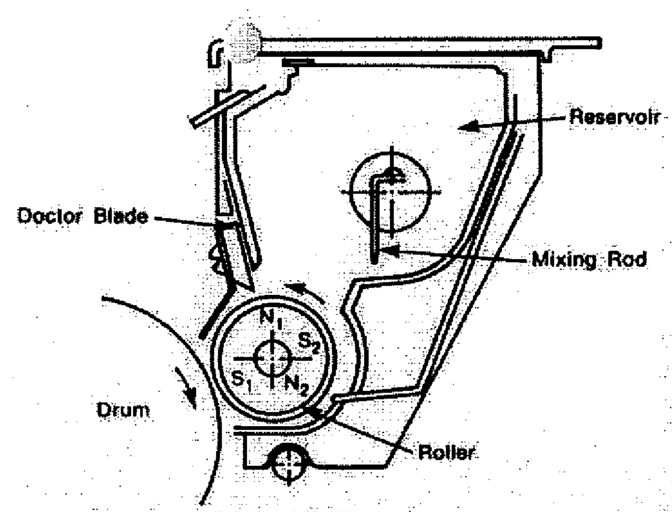


Fig. 8.10. Schematic of the Canon magnetic monocomponent development system. The roller rotates about stationary magnets, carrying magnetic toner past the doctor blade into the development zone [8.14]

The configuration used by Canon [8.14] is shown in Fig. 8.10. A roller (called a sleeve by Canon) rotates about stationary magnets in a reservoir (called a hopper by Canon) of magnetic, highly insulating, monocomponent toner. The toner is charged by contact with the roller and is carried out of the reservoir past a magnetic doctor blade. Evidence that the toner is charged against the roller was obtained by varying the coating material on the roller. Normally, for a metallic (aluminum) surface an electrostatic potential of the toner layer of −30 V was obtained. With different resins coated on the roller, values from +40 to −40 V were obtained. The doctoring process determines the amount of toner on the roller in the development zone. The magnetic doctor blade operates by splitting the toner chains where the spatial derivative of the magnetic field, which determines the toner-toner adhesion force, vanishes (Fig. 8.11).

Ricoh has discussed [8.15–17] a system, shown in Fig. 8.12, to charge nonmagnetic monocomponent toner triboelectrically. A supply roller made of foam pushes toner against a roller (called a development roller by Ricoh). Toner which adheres to the roller must pass under a spring-loaded metering blade. The source of toner charging has been determined by two experiments. First, *Demizu* et al. [8.15] determined that the counter charge is on the roller surface by measuring the electrostatic potential above the roller. Knowing the toner charge and the dielectric thickness of the roller, he predicted the electrostatic potential in the absence of the counter charge. If the counter charge is on the roller surface then the potential should be approximately zero. The data are consistent with the counter charge being on the roller surface, sug-

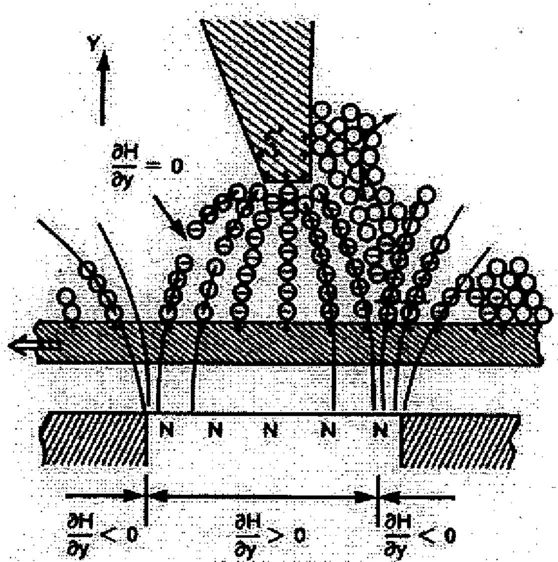


Fig. 8.11. The doctor blade in the Canon system is magnetic; the toner chains split where the force, proportional to $\partial H/\partial y$, vanishes [8.14]

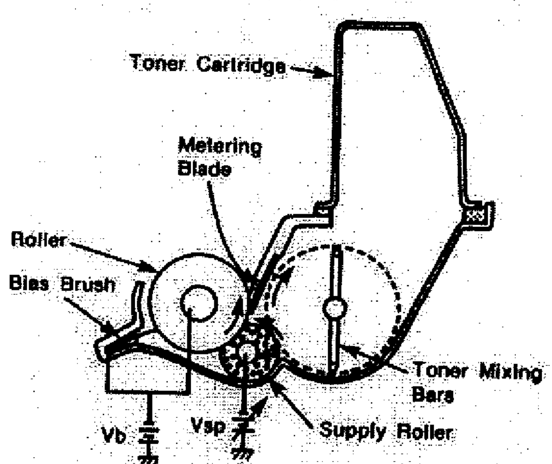


Fig. 8.12. Schematic of the Ricoh nonmagnetic monocomponent development system. Toner is pushed against the roller by the supply roller, where it obtains its charge. The toner is then metered before it contacts the photoreceptor (at approximately the 12 o'clock position) [8.15]

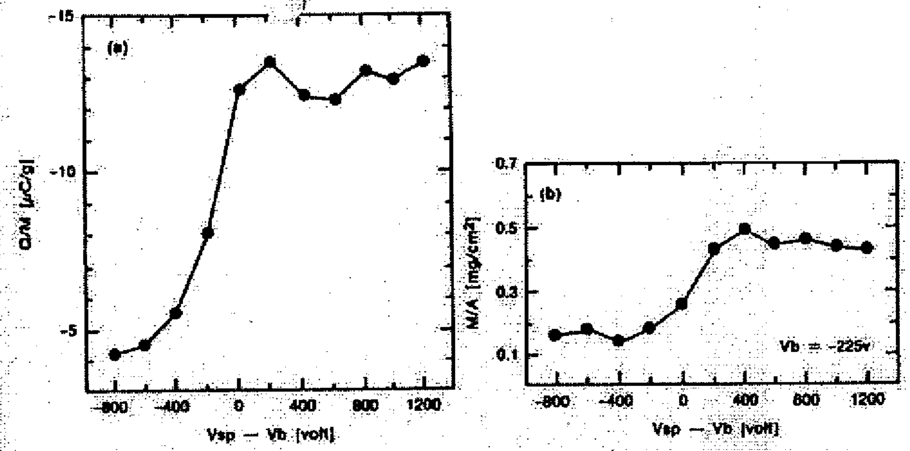


Fig. 8.13. The Q/M (a) and M/A (b) of the toner on the roller as a function of the potential difference between the roller and the supply roller [8.15]

gesting that the toner obtains its triboelectric charge by interacting with the roller surface. Second, the charge-to-mass ratio and M/A of the toner on the roller is measured as the potential between the roller and the supply roller is varied (Fig. 8.13). It is found that Q/M is independent of this potential difference and M/A increases between 0 and 400 V. Since M/A increases as the electric field increases it must be that the toner is charged and is probably being charged at the supply roller-roller interface. That Q/M is independent of bias suggests the charging process is independent of field, at least to the values used in the experiment. A method of measuring the individual toner particle's charge and radius appears to be available to the Ricoh group. Although the technique is not specified, data are shown (Fig. 8.14) which suggest that $Q \propto$

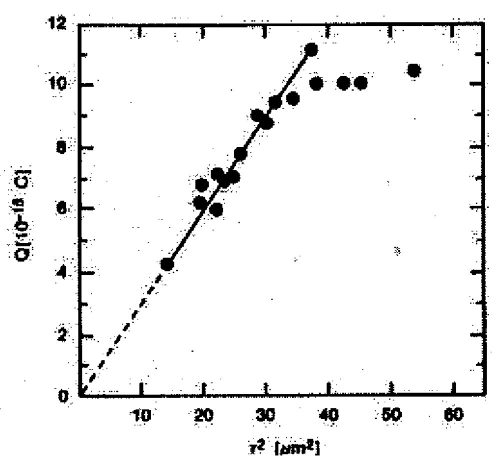


Fig. 8.14. Toner charge versus particle radius squared. Note $Q \propto r^2$ below $r = 6$ μm [8.15]

r^2 below $r = 6\,\mu m$. (Almost identical results were obtained by Terris et al., as discussed in Sect. 4.4.4). Above 6 μm radius, the toner charge tends to become independent of r. As the roller surface is insulating, means must be provided to discharge it. This is accomplished by a biased brush (Fig. 8.12) which contacts the roller after development occurs, at the 7 o'clock position.

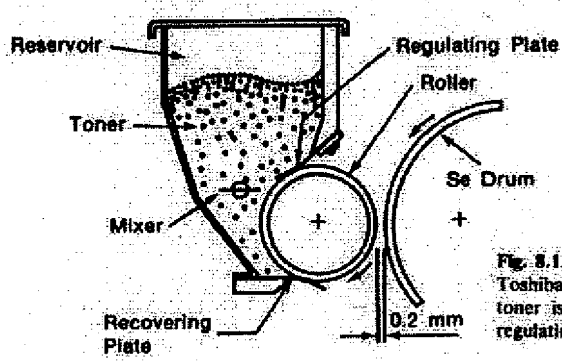


Fig. 8.15. A schematic diagram of the Toshiba development system. The toner is metered and charged by the regulating plate [8.18] (© 1985 IEEE)

At the same meeting at which Ricoh presented their results (see above) *Hosoya* et al. from Toshiba [8.18] presented their ideas for charging nonmagnetic insulating toner. Their apparatus is shown in Fig. 8.15. It is similar to the Ricoh design without the supply roller. A metering blade (called a regulating plate by Toshiba), by applying pressure to the roller, determines both the toner charge and the toner layer thickness. Detailed experimental analysis of the factors affecting toner charge were presented.

Both elastic metal and rubber plates were tried. Elastic metal such as stainless steel or phosphor bronze, 0.1–0.2 mm thick, was preferred because it did not deform with use and produced less wrong-signed toner. Plate pressure significantly affected the toner charge, as shown in Fig. 8.16. Higher pressures gave higher charge-to-mass ratios and less mass per unit area on the roller. Too high a pressure caused toner filming on the plate. Too low a pressure produced background development, i.e., probably wrong-signed toner. The recommended pressure was 100 g/cm for a 0.2 mm thick plate.

The roughness of the roller surface was also found to be an important variable. The toner charge-to-mass ratio and M/A on the roller as a function of mean roller roughness produced by sandblasting are shown in Fig. 8.17. Large roughness gave background, i.e., wrong-sign toner. Small roughness gave insufficient image density. A roughness of 0.7 μm was recommended. Toshiba maintained the surface roughness with use by catalytic nickel plating of the roller.

Carbon content of the toner was also varied and found to produce wrong-sign toner, due to "contact between the carbon at the surface of one toner and

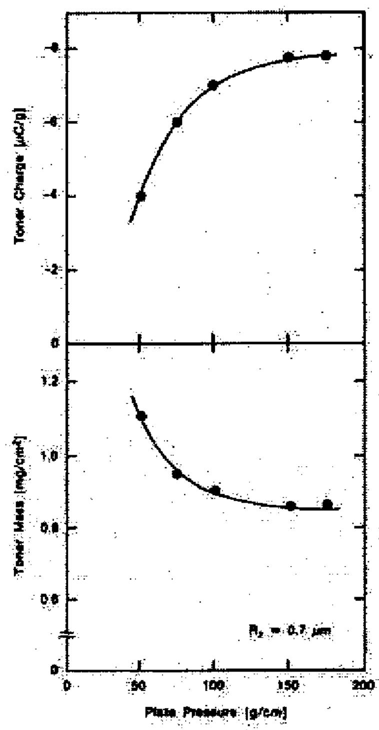


Fig. 8.16. Plate pressure affects the toner Q/M and M/A observed on the roller. Higher pressures increase Q/M and decrease M/A. The value R_z is the surface roughness of the roller (Fig. 8.17) [8.18] (© 1985 IEEE)

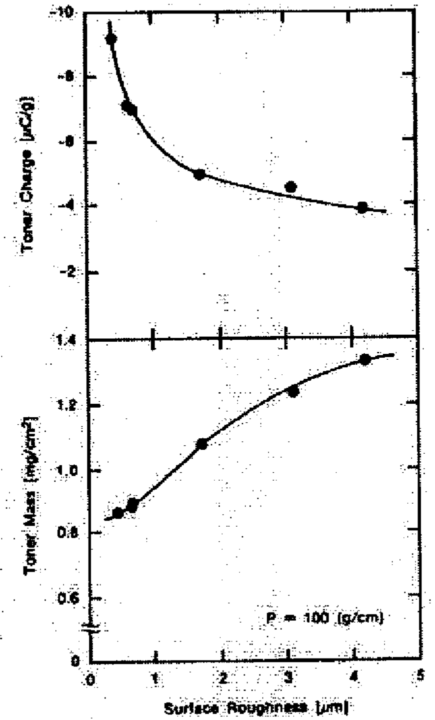


Fig. 8.17. The surface roughness of the roller also affects the toner Q/M and M/A on the roller. Larger roughness decreases Q/M but increases M/A [8.18] (© 1985 IEEE)

the polyester resin at the surface of another toner." Keeping the carbon content below 3% eliminated the background problem.

By measuring the current to the plate, it was determined that 30% of the toner charge is produced by friction with the plate and 70% by friction with the roller. Hosoya et al. observed a dc current which flows through the toner particles from the plate to the roller.

Patents have recently been issued for other nonmagnetic insulating monocomponent development systems, although none of these has been discussed in the scientific literature. For example, (1) *Gundlach* [8.19] of Xerox has recently suggested a triboelectric charging configuration in which the toner is forced through several wire screens of different meshes. (2) *Yoshikawa* of Canon [8.20] has suggested a modification to the Canon magnetic mono-

component system which converts it into a nonmagnetic system. Magnetic particles are confined between the roller and a magnetic doctor blade through which nonmagnetic toner flows, presumably charging against both the roller and the magnetic particles. (3) Fuji Xerox has claimed a contact metering blade which produces a uniform toner layer less susceptible to disruption by contaminants [8.21].

8.4 Corona Charging

Flint [8.22] patented a method of corona charging toner. He placed a corotron adjacent to a roller which attracted magnetically loaded toner. Corona charging was also used by *Chang* and *Wilbur* [8.23] in their studies of impression, i.e. contact, development. A supply of magnetic insulating toner is moved continuously around a roller past a corona charging device where ions generated by the corona are sprayed on the toner. Some obvious problems with this system are discussed by *Nelson* [8.7]. Corona devices are subject to toner contamination, especially by airborne toner, which will result in nonuniform ion emission along the length of the corona wire, and therefore nonuniform toner charging. Nonuniform ion emission is characteristic of negative corona (Sect. 2.1.1), which would make negative toner charging inherently nonuniform. Also continuous ion emission from the corona source coupled with the probability that individual toner particles will be moved past this source many times can result in time-dependent toner charge. Corona charging of particles and limitations on the amount of charge due to eventual repulsion of incoming ions has been discussed by *Hendricks* [8.24].

8.5 Charging Methods for Powder Coating

Electrostatic coating (painting) of surfaces with powders is a well-developed technology. The charging of insulating powders is accomplished during spraying by either corona charging or triboelectric charging (as the particles interact with the walls of the spray gun) [8.25]. A third potential source of charging, which may be operative in powder cloud development involves particle-particle charging. While the net charge may be zero, a distribution of charge about zero due to particle-particle contacts is likely.

8.6 Other Charging Methods

Hendricks [8.24] discusses other particle charging methods which have not yet been implemented in development systems. Particles can be charged by passage through an electron or ion beam. If the beam diameter is D_B and the

particle velocity is v, then the particle will be in the beam a time D_B/v. For a beam current density of J, the particle charge will be

$$Q = \frac{r^2 J D_B}{v}. \tag{8.3}$$

This is the maximum charge. If the potential of the particle becomes comparable to the beam energy, the electrons or ions will be repelled and further charging ceases. Also, secondary emission of electrons from the particle surface during electron charging can limit Q.

While not usually observed at room temperature, thermionic emission can charge particles. When the component of electron velocity in a direction perpendicular to the material surface becomes great enough to overcome the image force, the electron will leave the surface. This effect is relatively well understood and is employed in hot cathode vacuum tubes.

If light falls on the surface of a particle, the light quanta can transfer sufficient energy on impact to eject electrons from the particle. The available energy on impact is the photon energy less the work function of the material. In the range of visible light, very few materials exhibit photoelectric charging. However, ultraviolet [8.26] and x-ray charging are much more efficient due to lower reflection coefficients, higher surface absorption, and greater interactions with bound electrons which are easier to eject. This method obviously yields positive particles since electrons are ejected.

It has long been known that the cleavage of mica and other crystalline materials leaves the fresh surfaces charged. If the crystals are cleaved under vacuum, electrons with energies of hundreds of kilovolts are emitted. It has been suggested that a charged double layer at the separation surface is the location of the charges. When the double layer is disturbed or separated, high electric field intensities are produced and field emission of electrons can occur. Similar effects can occur during a process in which small particles are broken or torn from a surface, e.g. the manufacture of toner particles.

8.7 Traveling Electric Fields

In 1987, a nonmechanical means of transporting toner was patented by *Schmidlin* [8.27] and discussed by *Melcher* et al. [8.28]. The toner is placed on a linear array of spaced electrodes which are electrically wired to produce a traveling electric wave. The use of traveling electric fields to transport charged macroscopic particles was pioneered by *Masuda* [8.29,30] and is also being studied for agricultural applications [8.31]. The traveling electric wave can carry the toner, either in hops across the surface, synchronously with the electric field, or airborne, asynchronously with the electric field [8.28]. Toner is charged either prior to being placed on the electrodes or by interacting with

the surface which contains the electrodes. In the latter case, provision must be made to drain off the buildup of charge, by either surface or bulk conductivity whose value must be chosen so that the traveling electric field is not screened.

9. Monocomponent Development

While two component development (Chaps. 6 and 7) is today the predominant development system used in copiers and printers with speeds above 20 cpm (Table 1.1), it clearly is not the simplest system imaginable. For example, since toner is used but carrier is recirculated, means must be provided to sense depleted toner, and then to add and mix fresh toner. In addition, hardware must be built to recirculate a mixture of powders, of which only a small percentage of the weight (the toner) is directly used in creating marks on paper.

An obviously simpler development system is a monocomponent system in which the only powder component is toner. That concept was, of course, well known to the early inventors of electrophotography. The challenge is learning how to charge and transport the toner into the vicinity of the latent image. To date, at least four different monocomponent systems have been used in actual products (Sects. 9.1, 9.4–6). Because the relative simplicity compared to two component development implies fewer parts, smaller hardware, and lower manufacturing cost, monocomponent development systems have had their greatest application in low speed, low cost copiers. How far monocomponent development can penetrate the medium and high speed market is an important, unresolved question in electrophotography today.

Monocomponent development systems can be characterized by three independent choices: (1) The toner can be conductive or insulative. (2) The toner can be magnetic or nonmagnetic. (3) During development the toner, carried on a roller, can jump across a gap to the photoreceptor or be placed in simultaneous contact with the roller and the photoreceptor. Some people include a fourth choice in which the roller can run synchronously with or at a different speed from the photoreceptor. In this chapter we will consider the implications of these choices, as manifested in known development systems. Early work is discussed in Sects. 9.1 and 9.2. A theory of monocomponent development, which appears to be common to all published systems, is described in Sect. 9.3. In Sect. 9.4 the conductive toner system is described. Finally, the newest and most successful systems based on insulative toner are described in Sect. 9.5 (magnetic) and Sect. 9.6 (nonmagnetic). The current status of monocomponent development is summarized in Sect. 9.7.

9.1 Aerosol or Powder Cloud Development

One of the earliest monocomponent development systems that was used in a product was called aerosol or powder cloud development [9.1–7]. Work on this system was first mentioned in the mid-1950s [9.1–3]; a thorough study was reported by *Bickmore* et al. [9.4] in 1960 just at the dawn of the copier revolution and later by *Lewis* and *Stark* [9.5] in 1972. The objective of Bickmore et al. was to test the resolution capability of selenium photoreceptors. Resolutions in excess of 100 line pairs per millimeter were obtained using toner in the range of 0.1–0.8 μm diameter. Lewis and Stark's objective was to investigate the edge enhancement capabilities of this development system. The high resolution and the edge enhancement capabilities were exploited in the Xerox 125, an electrophotographic medical tool for obtaining x-ray pictures.

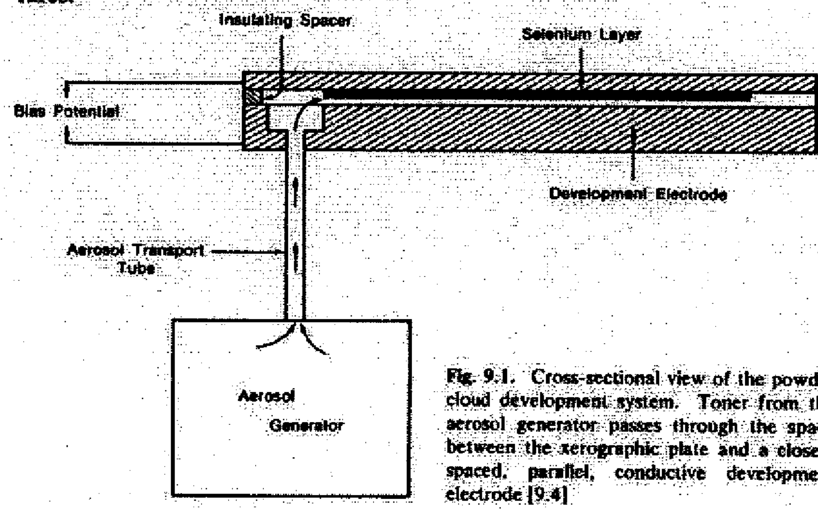


Fig. 9.1. Cross-sectional view of the powder cloud development system. Toner from the aerosol generator passes through the space between the xerographic plate and a closely spaced, parallel, conductive development electrode [9.4]

The system studied by *Bickmore* et al. [9.4] is shown in Fig. 9.1. In this configuration an electrode is present. Development to neutralization gave accurate reproduction of the gray scale, leading to copy quality similar to photographic film. Without an electrode or with a far-spaced electrode, toner responds to density gradients and is therefore especially sensitive to edges of solids and lines. It is this aspect of powder cloud development that was studied in [9.5].

In the system shown in Fig. 9.1, an aerosol generator lifts toner into a transport tube. The toner, suspended in air, is introduced into one end of a channel formed by a photoreceptor and an electrode. If the air flow is laminar then in the absence of electric fields the toner will not strike the walls. While the toner is probably close to electrically neutral on average, toner particles

possess charge equally distributed between positive and negative polarities. In the presence of an electric field due to the latent image, one polarity is attracted to the photoreceptor. This is one of the powder coating charging mechanisms discussed in Sect. 8.5.

The work reported by *Bickmore* et al. [9.4] was a detailed study of various effects of parameters on development. They found that a small electric field applied across the development zone was crucial. With no field the toner in the proximity of the photoreceptor was insufficient to cause complete development of edges. They found that 10–20 V across the few centimeters between photoreceptor and electrode usually led to complete development with "tolerable" background. Above 20V, background increased with little or no improvement in image completeness. By varying the development time (between 20 and 100 s) they showed that images were essentially completely developed in this system only when the fractional neutralization was 80% or higher (80 s). They also showed that the development rate was proportional to the potential difference in the development zone. Surprisingly, it was found that increasing the aerosol concentration by a factor of 100 had little effect on development time. Furthermore, higher aerosol concentrations produced images of poorer quality, containing missing sections, background, and streaks. The charge-to-mass ratio of the developed toner was found to significantly decrease, from 250 $\mu C/g$ to 60 $\mu C/g$ when the aerosol concentration was increased from 1 mg/l to 130 mg/l. It was suggested that toner space charge may be a factor in these effects.

The remarkable feature that was investigated by *Lewis* and *Stark* in 1972 [9.5] was the edge enhancement capability of this development system, of obvious practical importance in assisting doctors detect pathologies in x-ray pictures. What was observed was a white gap at the edge of lines and solids. The system investigated appears similar to the one studied by *Bickmore* et al., except the toner radius used was larger, 2 μm, leading to lower charge-to-mass ratios, 3–5 $\mu C/g$, and a far-spaced electrode (3.8 cm) was used. Cloud mass densities remained the same, approximately 6 mg/l.

The white gap (minimum in optical density) is shown in microdensitometer traces in Fig. 9.2 for a 30 V step. Data for a 3 V step were also given and it was claimed that even a 1 V step could be detected by eye. It was suggested that the source of this step is the geometry of the electric field, shown in Fig. 9.3, a phenomenon discussed by *Sullivan* and *Thourson* [9.8] in the cascade development literature (Sect. 5.3.1). Near a step the electric field lines arch back to the photoreceptor, penetrating only a small volume of space above the photoreceptor, unable to capture much toner. The width of the zone in which the field arches back on itself, the "forbidden zone", is compared with experiment in Fig. 9.4. Both figures show good agreement between theory and experiment.

As indicated above, this development system is in fact used commercially in the Xerox 125, an electrophotographic x-ray copier (Fig. 9.5). It was

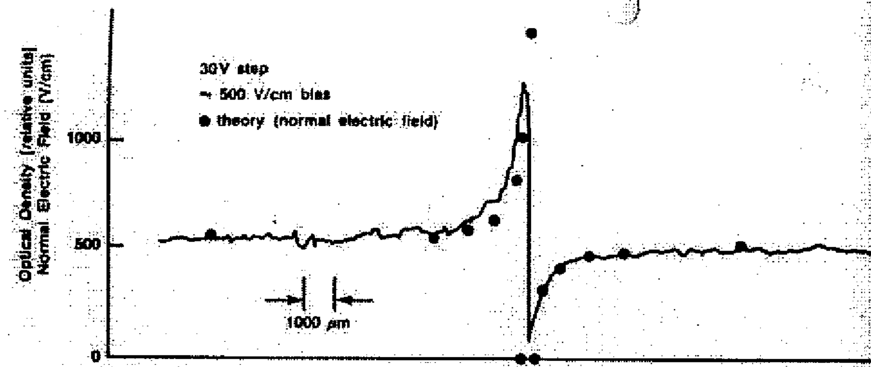


Fig. 9.2. A density trace across a 30 V step. The filled circles are a theoretical calculation of the normal electric field [9.5]

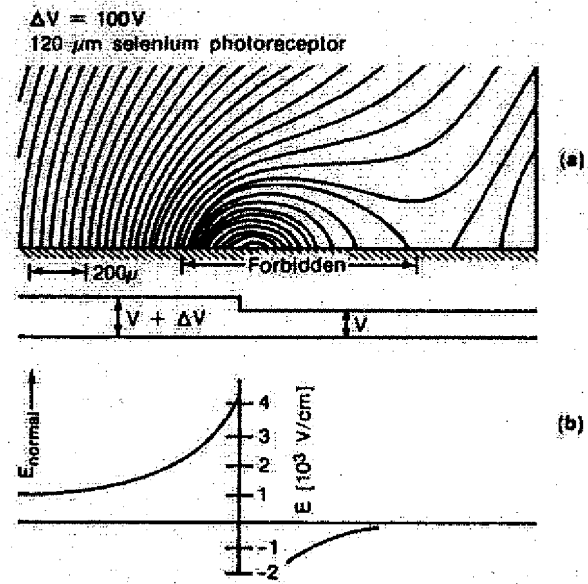


Fig. 9.3. The electric field pattern over a step in plate charge density (a) and (b) a plot of the normal component of electric field [9.5]

pointed out [9.6] that xeroradiography produces images with contrast sensitivities and resolutions at least equal to film, has short exposure-to-viewing time (about 30 s), and does not need a darkroom. However, its slow speed and high background characteristics make it unsuitable for high speed, high quality copiers.

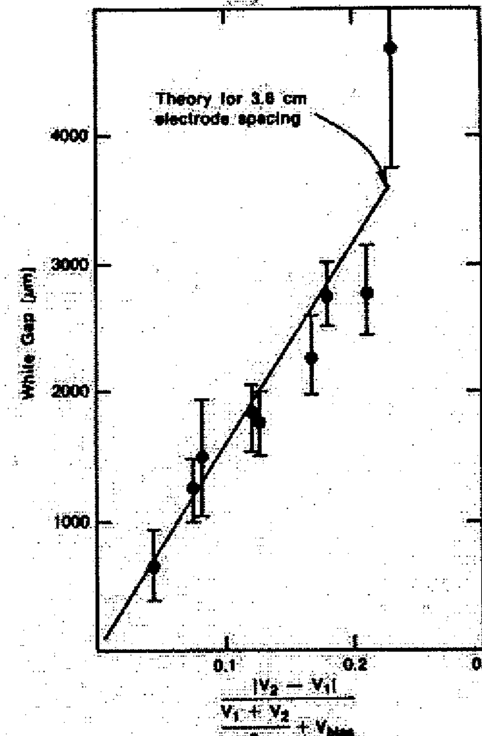
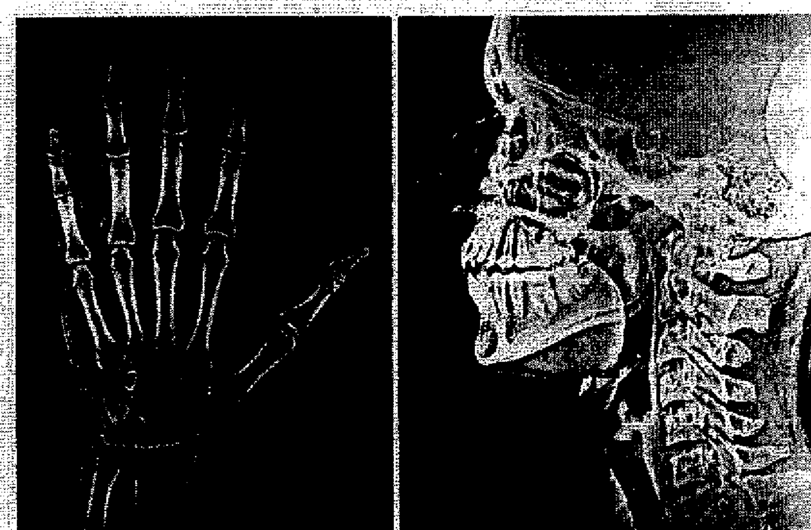


Fig. 9.4. Measured values of the white gaps at the edges of charge steps together with the results expected from a solution of the electrostatics problem. V_1 and V_2 are the voltages on either side of the step and V_{bias} is the potential on the counter electrode [9.5]

Fig. 9.5. Examples of Se plates exposed to x-rays developed with a powder cloud development system without an electrode (Courtesy of H. Bogdonoff of Xerox Corporation)



9.2 Early Work

Work on monocomponent development was begun in the early 1950s at Battelle as part of the effort to find a viable development system for an automatic electrophotographic copier [9.9]. An initial embodiment was a sheet of specially coated paper or rubberized cloth, called a donor, which was coated with a thin layer of toner by rubbing the toner over the surface with a cotton or fur pad. This triboelectrically charged and spread the toner in a thin layer. A charged photoreceptor could be developed by "touching down" the donor sheet on the plate momentarily (hence, the name touchdown development). Several such touchdowns were needed to produce high density images because of the sparce toner coating on the donor.

Thicker coatings of toner on the donor were obtained by various techniques. However, they usually produced background development, most likely because the toner was not sufficiently charged. Two new concepts were proposed to solve this density/background problem [9.9]. First, the donor was spaced 25–50 μm from the photoreceptor surface. Toner will jump across the narrow air gap to charged areas of the photoreceptor, but not to uncharged areas. This was given the name spaced touchdown. Second, a metal donor cylinder (which we call a roller in this book) was loaded with toner by powder cloud deposition techniques (Sect. 9.1) and then corona charged. This remained a slow process because of the roller loading step.

Work on monocomponent development also was being pursued at RCA. In 1957 a patent was issued to *Greig* [9.10]. He suggested loading a roller with toner which is then contacted to the charged photoreceptor. The roller material can be hard or soft, insulator or conductor. The toner is held on the surface either electrostatically or by tackiness. If the roller is conductive, then the toner can be corona charged; if an insulator, by triboelectricity. The toner should be a material with "good dielectric properties, such as sublimed sulfur." Mention is made of doctoring the toner on the roller.

In 1958, Wilson, president of Haloid Xerox (the name of the Xerox Corporation at the time), suggested using insulative magnetic toner in a monocomponent system [9.11]. The magnetic toner is picked up from a toner reservoir by many circular magnets which are adjacent to each other, forming magnetic brushes. The magnets rotate, continuously bringing fresh toner to the latent image.

In 1959, *Mayo* [9.12] of Battelle suggested using a belt which passes through a reservoir of toner as a development "roller". He assumed triboelectric charging of the toner will occur and suggested coating the belt with known carrier-coating materials. He recommended contact development and speed ratios greater than one.

The first conductive toner monocomponent development patent was issued to *Gundlach* [9.13] of Xerox Corporation in 1965. The charging method is clearly induction, allowing a straightforward solution to the toner charging problem. The toner is loaded onto the conductive donor surface by directing a powder cloud at the surface. The toner will adhere either due to van der Waals forces or electrostatically if charged by, for example, "feeding at turbulent rates through fine tubes." The conductive toner on the conductive donor surface is then pressed into contact with the latent image. The toner is charged inductively by the electric field of the latent image and then adheres to the latent images. It was pointed out that this system should have no threshold voltage for development.

In 1966, *Willmott* [9.14] of IBM was issued a patent which claims development from a belt which is spaced a distance from the photoreceptor. This work follows from an earlier patent by *Lowrie* of IBM [9.15] in which a spaced touchdown system is described. Toner is attracted across the space only when an electrostatic image exists on the photoreceptor. Where no electrostatic image is present, no toner touches the photoreceptor, leading to low background. Toner is loaded onto a belt which is dipped into a reservoir of toner. Speed ratios less than one are suggested.

Battelle continued work on what they called spaced touchdown development. Apparently Mayo's concept of running a belt through a toner reservoir did not adequately load and charge toner since *Andrus* et al. [9.9] of Battelle reported at the Second International Conference on Electrophotography in 1974 on a microfield donor (which we will call a roller). This roller consisted of an aluminum cylinder coated with 25 μm thick insulating enamel over which a copper screen was created. The 150 mesh copper screen pattern was created by standard photoresist and etching techniques. By impressing 200 V between the aluminum and copper, small microelectric fields were created which attracted toner of both signs from a reservoir of fluidized toner. This toner layer was then corona charged to give the toner the same polarity and charge level. The roller was spaced 25–50 μm from the photoreceptor with shims at the ends of the roller. Reverse biasing to decrease background was used. It was observed that the corona charging step adds sufficient charge to the insulating squares between the copper screen to bring the whole roller substrate to an equipotential, preventing further reloading. Hence, a neutralizing corona discharge of the roller before reloading is necessary. The Battelle group report excellent solid areas (remember, they were comparing their results to cascade development!), good resolving power (8–10 line pairs per millimeter), but a high gamma, i.e., high contrast, making the process not suitable for continuous tone images. Studies of the sensitivity of copy quality to spacing revealed that below 25 μm unsatisfactory images were produced because the toner loading was generally not sufficiently uniform. Above 75 μm spacing, image density dropped and the ability to reproduce fine lines and dots was reduced. This clearly created a challenging tolerance problem.

At the same meeting in 1974, *Chang* and *Wilbur* [9.16] of IBM reported on another version of monocomponent development, which they called impression development. In this system they attempted to coat a roller with a

material (a copolymer of vinyl chloride and vinyl acetate) which triboelectrically charged the toner. To allow the coating to discharge, it was loaded with 30% carbon to give it appropriate conductivity. The carbon also gave the surface a roughness of ≈4 µm which the authors suggested enhanced triboelectric charging on the toner. The toner was held in a reservoir against the roller and was doctored with Teflon blades to 2 or 3 monolayer thickness. A corona recharge was required to "improve the uniformity of the charge distribution." This roller was then contacted to the photoreceptor at synchronous speeds. "Good" resolution (5 line pairs per millimeter), solid areas and line copy were reported. As reported by Battelle, high gammas were observed.

The interested reader can find a more complete list of monocomponent patents up to 1972 in *Schaffert's* book, *Electrophotography* [9.17].

9.3 Theory of Monocomponent Development

In Sects. 9.4–6, monocomponent development systems which have been successfully implemented in automatic copiers are described. In reviewing this literature it became apparent that concepts used by the various authors could be combined in a universal theory of monocomponent development, which is described below.

As with theories of two component development systems, our goal is to express the developed mass per unit area as a function of the measurable hardware and material parameters of the system. We will assume for this discussion that the toner has been uniformly doctored and charged on a roller (Chap. 8) and brought into the vicinity of the latent image. After proposing this theory, it will be applied in the following sections to available monocomponent development experimental data. The theory might be called "field stripping from a finite source".

In a monocomponent development system, the toner adheres to the roller by electrostatic F_{es} and magnetic forces (for magnetic toner) F_M. This adhesion must be overcome by the Coulomb force caused by the electric field E_{air} of the latent image (Fig. 9.6a). Therefore a threshold electric field E_{th} is predicted (Fig. 9.6b) below which development is zero:

$$Q_t E_{th} = F_{es} + F_M . \tag{9.1}$$

Expressions for all three terms have been derived before or are well known. The electric field acting on toner in air is related to the electrostatic potential of the latent image V, any bias potentials V_{bias} on the roller, the dielectric thickness of the photoreceptor d_s/K_s, the air gap L, and the developed toner dielectric thickness d_t/K_t.

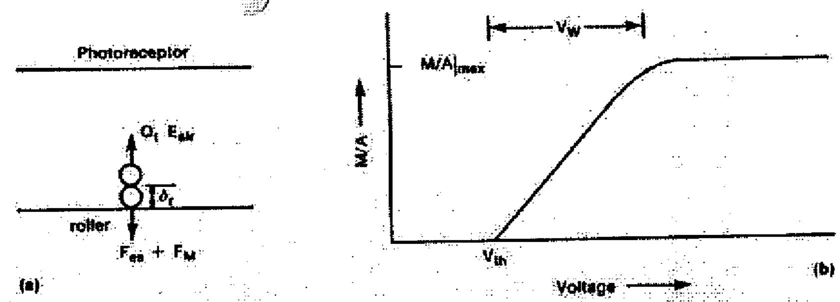


Fig. 9.6. a A universal theory of monocomponent development is proposed based on the forces experienced by toner. b This theory predicts a voltage threshold and a maximum mass per unit area. The voltage width V_W of the rising portion of the curve is determined by the toner adhesion distribution

$$E_{air} = \frac{V - V_{bias}}{d_s/K_s + L + d_t/K_t} . \tag{9.2}$$

The electrostatic adhesion of toner to the roller is the image force

$$F_{es} = \frac{1}{4\pi\varepsilon_0} \frac{Q_t^2}{(2r + \delta_r)^2} \tag{9.3}$$

plus any van der Waals adhesive forces. In (9.3) we have allowed for the fact that the bottom of the toner particle may be spaced a distance δ_r above the roller surface because it is above the first monolayer (Fig. 9.6a). The magnetic adhesion is given by [9.18]

$$F_M = \frac{\mu - 1}{\mu + 1} r^3 \bar{H} \cdot \nabla \bar{H} , \tag{9.4}$$

where μ is the permeability of the toner, r is the toner radius, $\bar{H}$ is the magnetic field and $\nabla \bar{H}$ the spatial derivative of the magnetic field. Solving for $V - V_{bias}$ and labeling it as a threshold voltage V_{th} gives

$$V_{th} = \left(\frac{d_s}{K_s} + L + \frac{d_t}{K_t} \right) \times \left(\frac{1}{4\pi\varepsilon_0} \frac{Q_t}{(2r + \delta_r)^2} + \frac{\mu - 1}{\mu + 1} \frac{r^3 \bar{H} \cdot \nabla \bar{H}}{Q_t} \right) . \tag{9.5}$$

As V is increased above V_{th}, toner is field stripped from the roller. If all of the parameters were a single value, a step function development curve would result. Clearly the toner charge and radius are distributed parameters.

Furthermore δ_r, the distance of the bottom of the toner from the roller surface, can vary if more than one monolayer is present. The value of $\overline{H} \cdot \nabla \overline{H}$ can vary in the development zone both in the direction toward the photoreceptor and along the development width. These effects produce a width V_w of the development curve (Fig. 9.6b).

As the roller is usually loaded with only a few monolayers of toner, the developed mass per unit area reaches a maximum when all of the toner is used up:

$$\left.\frac{M}{A}\right|_{\max} = \left.\frac{M}{A}\right|_{\text{roller}} r, \tag{9.6}$$

where r is the ratio of the roller to the photoreceptor velocities and represents the length of roller that contacts a unit length of photoreceptor (6.63).

The predicted development curve, i.e., mass per unit area versus voltage, is shown in Fig. 9.6b. This theory of monocomponent development might be called field stripping (since the electric field strips toner from the roller) from a finite source (the source of toner is limited to the few monolayers on the roller).

Inspection of Fig 9.6b immediately indicates that monocomponent development systems have nonlinear development characteristics that will affect the gray scale reproduction characteristics. For example, under the condition that the voltage width is small compared to the threshold, the development curve approaches a step and only whites and blacks are reproduced. This characteristic is usually described by gamma, the slope of a D_{out} (output density) versus D_{in} curve. Gamma differs from 1, the ideal for perfect gray scale rendition, due to nonlinear transfer functions in a system, such as given by the development curve shown in Fig. 9.6b.

In these systems an ac voltage V_{ac} is sometimes superimposed on the dc voltages of the latent images. This adds an additional time-dependent force to (9.1). One proposal for the effect of V_{ac} [9.19] predicts a change in slope of M/A versus V. As the effect of V_{ac} appears to affect the threshold voltage more strongly (see below), the following alternative picture is proposed. The force balance on toner attracted to the roller and photoreceptor is shown in Fig. 9.7. In Fig. 9.7a is shown the half cycle in which V_{ac} causes a force towards the photoreceptor. If the force pulling the toner towards the photoreceptor overcomes the adhesion force, toner will develop (the Canon [9.19] literature uses the word "project") towards the photoreceptor. During the next half cycle, the force due to the ac voltage is in the opposite direction (Fig. 9.7b). The same logic applies. Hence, for high enough frequency the toner will "project" back and forth.

As the roller rotates and L increases past the center of the development zone the forces due to the applied voltages will decrease. Where the toner ends up will depend upon which force condition is largest when projection stops. If

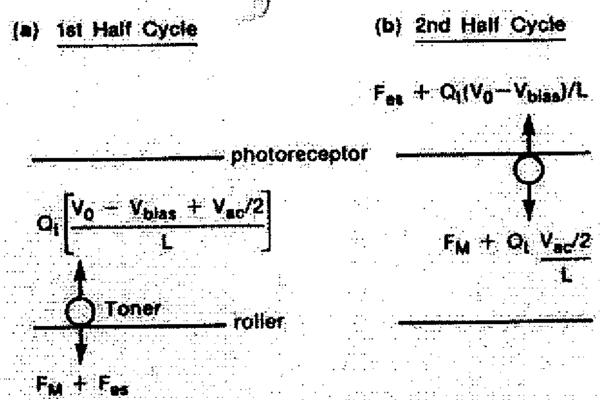


Fig. 9.7. The effect of ac bias on development characteristics is to introduce a time-dependent force which "projects" the toner from both the photoreceptor and the electrode. Shown are the forces on toner particles during each half cycle of the ac voltage

$$Q_t\left(\frac{V_0 - V_{\text{bias}} - V_{\text{ac}}/2}{L}\right) - (F_M + F_{\text{es}}) > \left(F_M + \frac{Q_t V_{\text{ac}}/2}{L}\right) - \left(F_{\text{es}} + \frac{Q_t(V_0 - V_{\text{bias}})}{L}\right) \tag{9.7}$$

then toner ends up on the photoreceptor. This is just

$$\frac{Q_t(V_0 - V_{\text{bias}})}{L} > F_M, \tag{9.8}$$

a condition independent of V_{ac}. It is of course possible that the imposition of V_{ac} increases the width of the development zone, moving the last projection to regions where the magnetic force is lower. This makes F_M a function of V_{ac} and can lead to increased development,

$$\frac{Q_t(V_0 - V_{\text{bias}})}{L} > F_M(V_{\text{ac}}). \tag{9.9}$$

Such an effect suggests that the precise shape of the magnetic field and its spatial distribution at the edges of the development zone could be important in determining the development characteristics. Note also that F_{es} is missing from (9.8). Because the toner is now airborne most of the time, it is far from the roller and photoreceptor, making the electrostatic adhesion force zero. This predicts that the threshold voltage, in the presence of a V_{ac} large enough to cause projection, will be reduced, i.e., $F_{\text{es}} = 0$ in (9.1).

It is mentioned by both Canon [9.19] and Toshiba [9.20] that use of V_{ac} in development systems with a gap improves the edges of lines. A reason for this may be that F_{es}, the toner image force to the roller, is eliminated from the physics by the "projection" condition. Development of toner onto edges from a powder cloud (generated during projection) should be more uniform than from a roller in which adhesive bonds need to be broken.

Line to solid density ratios for these development systems should approach 1 as the roller-photoreceptor spacing approaches the photoreceptor dielectric thickness and the line to solid area electric field ratio approaches 1. Line to solid area ratios will also approach 1 if the available toner on the roller is used up. *Sakamoto* et al. [9.21] discuss a novel geometry in which thin, floating, metal electrodes are placed on the roller surface. They argue theoretically that this enhances the electric fields for line development, although no supporting experimental data are given. It is shown in [9.21] that solid area density decreases as the distance to the roller increases, as expected.

Discussions of mechanisms of background development for monocomponent systems are not available. It is obvious that the magnetic force (for magnetic toner) and reverse biasing (for correct sign toner) aid in removing background toner.

9.4 Conductive Toner

The first monocomponent development system for an automatic copier was introduced in a product by 3M in 1971 [9.22]. It used magnetic, conductive toner that was charged inductively in the development zone. A schematic of this system, taken from *Kotz*'s patent [9.22], is shown in Fig. 9.8. The magnetic toner is metered onto a roller and held by magnetic forces. The toner is moved around the roller, spaced approximately 750 μm from the photoreceptor, by rotating either the magnets or the roller. In the development zone the toner contacts the photoreceptor. The charge of the latent image initially creates an electric field in the conductive toner. Charges flow from the roller down the toner chains (formed in response to the magnet fields) to neutralize this field. With sufficiently conductive toner, the charge moves to the monolayer of toner immediately adjacent to the photoreceptor.

The above qualitative discussion is sufficient to identify the threshold voltage and the maximum development [from (9.1) and (9.6)]. The threshold voltage is found by finding the threshold electric field from the force condition

$$Q_t E_{th} = F_M. \tag{9.10}$$

The electrostatic adhesion of toner to the adjacent toner layers is ignored because it is cancelled to first order by the same force to the photoreceptor. Since the toner charge per unit area σ_t equals the photoreceptor charge per

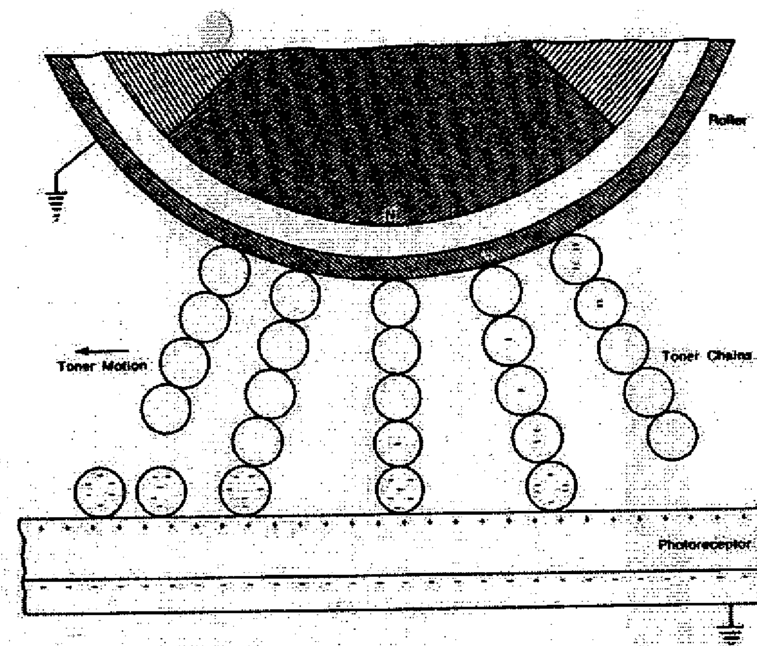


Fig. 9.8. Conductive toner is charged by induction. Charge flows down the toner chains in response to the electric field of the latent image [9.22]

unit area σ_p in an inductively charged system,

$$\sigma_t = \sigma_p, \tag{9.11}$$

$$\frac{Q_t}{\pi r^2} = \frac{V\varepsilon_0}{d_s/K_s} \quad \text{and} \tag{9.12}$$

$$E_{th} = \frac{V_{th}}{d_s/K_s}, \tag{9.13}$$

we obtain

$$V_{th}^2 = \frac{F_M(d_s/K_s)^2}{\varepsilon_0 \pi r^2} \quad \propto \; r, \tag{9.14}$$

since $F_M \propto r^3$, (9.4). Kotz claims $F_M \approx 10^{-4}$ dynes, giving a threshold voltage of 36 V for $d_s/K_s = 10\mu$m and $r = 10\ \mu$m. Larger diameter toner particles are used in conductive systems because the threshold voltage depends on their radius [see (9.14) and below]. (For the reader who chooses to check the calculations in this chapter it is useful to recall that there are 10^5 dynes per newton and 1 N = 1 CV/m.)

The maximum development is a monolayer of toner and is independent of speed ratio since any toner in the second layer which has charge will immediately transfer its charge to toner in the first layer to null the electric field:

$$\frac{M}{A}\bigg|_{\max} = \frac{M}{A}\bigg|_{\text{monolayer}} = \frac{4}{3} r \rho_t p_t \tag{9.15}$$

where r is the toner radius, p_t is the toner mass density and ρ_t is the toner surface packing. For $r = 10\,\mu\text{m}$, $\rho_t = 1\,\text{g/cm}^3$, $p_t = 0.6$, (9.15) gives $M/A|_{\max} = 0.8\,\text{mg/cm}^2$. That $M/A|_{\max}$ is independent of the speed ratio, and that $M/A|_{\max}$ is approximately $1\,\text{mg/cm}^2$ have been demonstrated by *Nelson* [9.23] and *Shimada* et al. [9.24,25] (Figs. 9.9 and 10).

When the potential difference across the development zone is below V_{th}, i.e. in the background regions, toner will not develop as long as F_M for all the toners is kept large enough. This begins to define the control required on the

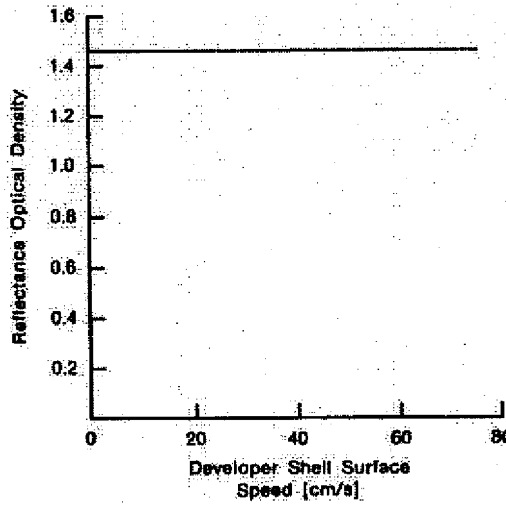


Fig. 9.9. For conductive toner, the maximum mass per unit area is independent of speed ratio [9.23]

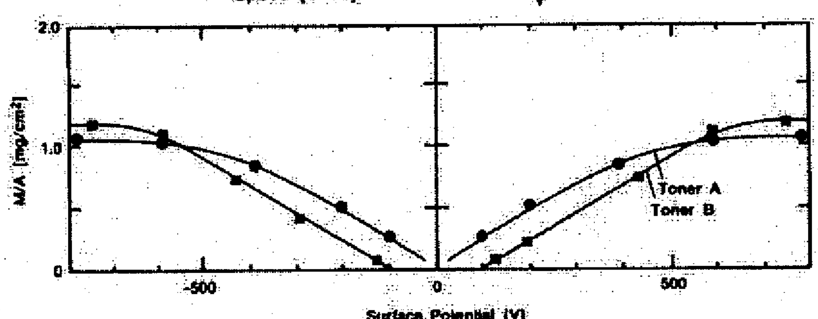


Fig. 9.10. Developed toner density versus potential of photoreceptor for conductive toner. Note that toner development is polarity independent and peaks at 1 mg/cm² [9.24]

amount of magnetite in each particle and the size distribution allowed. Clearly, small particles will be a potential source of background toner (9.14).

The question of conductivity control is an interesting one. *Field* [9.26] states that the toner should charge in a few microseconds, requiring conductivities of $10^7\,\Omega\,\text{cm}$. Such short charging times compared to development times (milliseconds) limit development to one monolayer. One could increase development by making the charging time approximately equal to the time the toner is in the development nip, so that some charge remains on toner above the monolayer adjacent to the photoreceptor. However, due to variation in conductivity down each chain, uniformity and reproducibility would probably suffer.

Another prediction for inductively charged toner is that development should be independent of polarity. The full development curve for both polarities was published by *Shimada* et al. [9.24,25]. Their data are shown in Fig. 9.10. Note M/A saturates at about $1\,\text{mg/cm}^2$ in agreement with (9.15), the developed characteristics are independent of the polarity of the surface potential, and a small threshold voltage is observed for toner B.

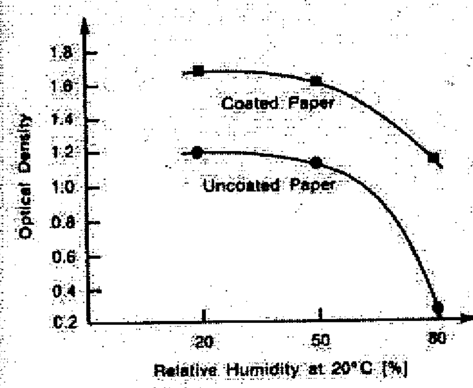


Fig. 9.11. Line density with conductive magnetic toners (volume resistivity: $10^8\,\Omega$ cm) versus relative humidity [9.27]

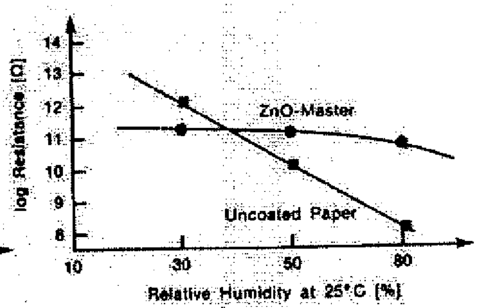


Fig. 9.12. Surface resistance of various papers (at 1 kV) versus relative humidity [9.27]

The two problems with conductive toner are now well known [9.27]. First, as discussed above, only a monolayer of toner can be developed on the photoreceptor for sufficiently conductive toner. Second, and perhaps more seriously, under high relative humidity conditions, it is found that the optical density decreases (Fig. 9.11). This occurs because under high relative humidity conditions paper becomes conductive (Fig. 9.12) and the toner charge, but not the toner, is transferred to paper at the transfer station.

Conductive monocomponent development is currently being used by two companies, Delphax and Océ. Delphax makes printers based on ionography,

as discussed in Sect. 1.4.2. They transfer and "fix" the toner in one step, a high pressure "transfix" station. The toner is mechanically transferred and pressed into the paper, eliminating the need for electrostatic transfer. Océ uses a double transfer system in their copiers in which the toner is transferred to a warm intermediate belt before being transferred to paper. A thermal transfer is used in place of an electrostatic transfer.

9.5 Magnetic, Insulative Toner

For this system, we assume uniform charging and doctoring of a few monolayers of the toner on a roller has been accomplished prior to the toner entering the development nip region (Sect. 8.3). Since Q_t is fixed, we can directly use (9.5) and (9.6):

$$V_{th} = \left(\frac{d_s}{K_s} + L + \frac{d_t}{K_t}\right)\left(\frac{1}{4\pi\epsilon_0}\frac{Q_t}{4(r+\delta_r)^2} + \frac{F_M}{Q_t}\right), \tag{9.16}$$

$$\left.\frac{M}{A}\right|_{max} = \left.\frac{M}{A}\right|_{roller}. \tag{9.6}$$

The first commercial implementation of this process was achieved by 3M in 1977 [9.23]. Discussions of the charging mechanism were given in Sect. 8.2. Unfortunately, few results have been published on the development characteristics of this system. *Nelson* [9.23] shows M/A increases with r, but it is not clear whether $M/A|_{max}$ was measured, or whether Q_t is increasing with r (Sect. 8.2), shifting the threshold down, as would be predicted for a dominant magnetic adhesion, the last term in (9.16). (Nelson argues the latter is occurring.)

Published data from the impression development work [9.16] verify the general features of (9.16) and (9.6). Copy reflection density versus contrast voltage has a threshold (of about 25 V) and M/A saturates above 150 V.

By far the most successful implementation of the magnetic, insulating toner, monocomponent development system is practiced by Canon [9.19]. This system is used in their whole line of copiers from the 6 cpm personal copier all the way up to a 70 cpm copier (Table 1.1). A schematic is shown in Fig. 8.10. As discussed in Sect. 8.3, charging and doctoring are done by frictional contact with the roller and with a magnetic doctor blade.

In the development zone the photoreceptor is spaced 300 μm from the roller surface so the toner has to "jump" across an air gap to develop onto the photoreceptor. The speed ratio is set at 1. A development curve is shown in Fig. 9.13. It has the now familiar voltage threshold and saturated optical density. The copy density saturation, about 1.2 OD, corresponds to (from

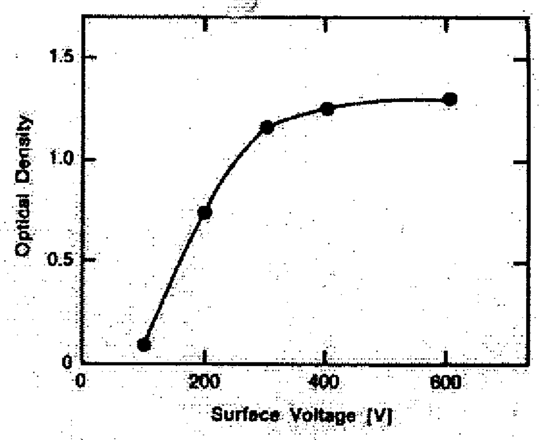


Fig. 9.13. Developed solid area density as a function of surface voltage without ac bias voltage for the Canon magnetic insulating monocomponent development system [9.19]

[Ref. 9.19; Fig. 7]) 0.5 mg/cm^2, very close to what would be expected for one monolayer of 5 μm radius toner, see (9.6), a speed ratio of 1, and $\rho_t = 0.6$:

$$\left.\frac{M}{A}\right|_{max} = \left.\frac{M}{A}\right|_{roller} r \to \frac{4}{3} r\rho_t p_t = 0.4\ \mathrm{mg/cm^2} \quad \text{(monolayer)} \tag{9.17}$$

It is indicated in [9.19] that in the development zone the toner layer thickness is 100 μm, which must represent the height of the magnetic brushes. The toner particles at the top of the bristles are very far from the roller surface and the primary attractive force between toner and roller is the magnetic adhesion. The threshold voltage is then given by, see (9.16),

$$V_{th} = \left(\frac{d_s}{K_s} + L + \frac{d_t}{K_t}\right)\left(\frac{F_M}{Q_t}\right). \tag{9.18}$$

For $F_M = 0.34 \times 10^{-4}$ dynes, $Q_t = 1.5 \times 10^{-15}$ C, and $L + d_s/K_s + d_t/K_t = 300$ μm as given in [9.19], (9.18) predicts $V_{th} = 70$ V, very close to the observation.

In the Canon paper the voltage width (V_w in Fig. 9.5) is estimated by assuming that all of the toner particles have one charge and one radius. Further, it is assumed that the last toner particle to be developed, a toner particle immediately adjacent to the roller, experiences an image force due to the image charges of all the toner originally on the roller, i.e., the whole layer is developed at once. In this case the additional electrostatic adhesion of a toner in the first monolayer adjacent to the roller is proportional to Q_t times the charge per unit area σ_t of the rest of the toner, or

$$F_{es} = Q_t \frac{\sigma_t}{K_t \epsilon_0} = Q_t \rho_{tv} d_t / K_t \epsilon_0, \tag{9.19}$$

which is the second term in [Ref. 9.19; Eq. (11)]. For $K_t = 1$ (because toner packing is so low when $d_t = 100\,\mu$m), $Q_t = 1.5 \times 10^{-15}$ C and $\rho_{tv} = 4 \times 10^{-2}$ C/m^3 this is about 2 times F_M, suggesting an additional voltage of 2 times V_{th}, or 140 V, is required to develop all the toner. This corresponds closely to the observation (Fig. 9.13).

Another approach to this calculation is to assume the last toner particle experiences only the electrostatic adhesion due to its own image charge. This adds

$$\frac{1}{4\pi\varepsilon_0}\frac{Q_t^2}{4r^2} \tag{9.20}$$

to the adhesion force, which equals 0.2×10^{-4} dynes (for $r = 5\,\mu$m), requiring an additional 40 V to completely develop the toner. The experiments indicate approximately 200 V extra is needed, possibly indicative of the existence of higher charge or smaller radius toner or larger magnetic forces near the roller surface, all reasonable possibilities.

In addition to the dc bias, Canon uses ac biases to assist in development. Data are shown in Fig. 9.14 for $V_{ac} = 800$ and 1400 V and two frequencies, 500 and 1000 Hz. The lower scale is the total dc potential across the gap, $V_0 - V_{bias}$. It can be seen that the addition of V_{ac} has substantially lowered the threshold (from 100 V, Fig. 9.13, to zero for $V_{ac} = 800$ and -100 V for $V_{ac} = 1400$ V at 500 Hz), as predicted qualitatively in Sect. 9.3.

Frequencies too high for the toner to follow obviously will be less effective. The higher threshold at 1000 Hz compared to 500 Hz probably reflects this since, as *Takahashi* et al. [9.19] note, the toner transient time T across the gap L is

$$T = \sqrt{\frac{2M_tL^2}{Q_tV}}\,, \tag{9.21}$$

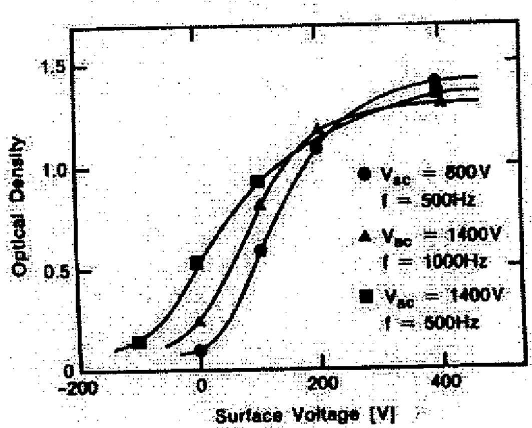


Fig. 9.14. Developed solid area density as a function of surface voltage for different ac bias conditions (V_{ac} is the peak-to-peak voltage) for the Canon magnetic insulating monocomponent development system. The voltage axis has been recalculated including the bias potential of 200 V [9.19]

which equals 0.21 ms for $L = 300\,\mu$m, $Q_t = 1.5 \times 10^{-15}$ C, $V = 1400$ V and $M_t = 5.4 \times 10^{-10}$ g.

No data characterizing line development, line/solid ratios or background development have been published on this system.

9.6 Nonmagnetic, Insulative Toner

In 1985 at the IEEE-IAS Conference in Toronto both Ricoh [9.21,28,29] and Toshiba [9.20,30] announced a *nonmagnetic* insulating toner monocomponent development system. In the Ricoh system the roller with toner contacts the photoreceptor. In the Toshiba system the toner must jump a gap. Charging in the Ricoh system was described in Sect. 8.3. No development data for this system have been published by Ricoh. This system is commercially available in the colored toner cartridges for the Ricoh RePRO jr. copier (8 cpm) and in their PC Laser 6000 printer (6 ppm).

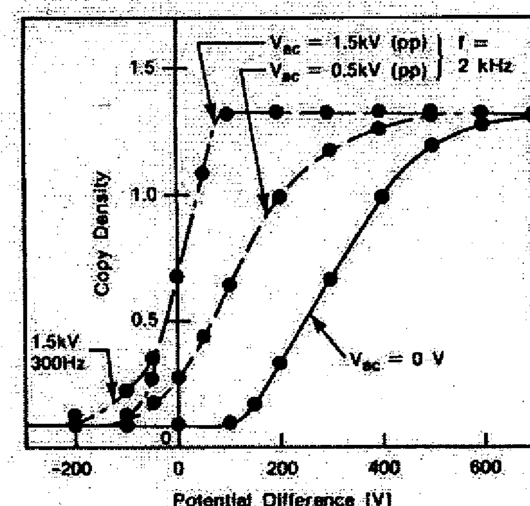


Fig. 9.15. Developed solid area density as a function of potential difference between the roller and the photoconductor for various ac bias conditions for the Toshiba nonmagnetic insulating toner monocomponent development system [9.20] (© 1985 IEEE)

The Toshiba system is shown in Fig. 8.15. The hardware variables which control toner charging were discussed in Sect. 8.3. The development characteristics are shown in Fig. 9.15. With $V_{ac} = 0$, the now familiar voltage threshold, rise, and saturation are observed. With no magnetic force, the threshold is now entirely due to the Coulomb force required to overcome the electrostatic adhesion, i.e., from (9.5),

$$V_{th} = \left(\frac{d_s}{K_s} + L + \frac{d_t}{K_t}\right)\frac{1}{4\pi\varepsilon_0}\frac{Q_t}{4r^2} \approx \frac{L}{4\pi\varepsilon_0}\frac{Q_t}{4r^2}\,, \tag{9.22}$$

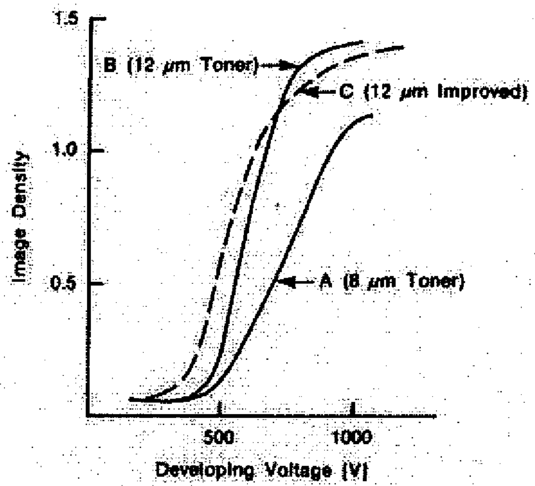


Fig. 9.16. Development curve for the Toshiba nonmagnetic insulating toner monocomponent development system for different size toner particles [9.30]

which is predicted to be 66 V for the parameters given by the Toshiba workers ($L = 0.2$ mm, $Q/M = 7\,\mu C/g$, and we will assume $r = 5\,\mu m$) in good agreement with the observations.

The effect of V_{ac} is to shift the threshold for $V_{ac} = 500$ V and to steepen the curve for $V_{ac} = 1500$ V. In the absence of a magnetic retaining force, the application of a large ac field should reduce the toner adhesion to the roller to zero, see (9.22), suggesting all toner should develop at zero volts. The data taken with $V_{ac} = 1500$ V appear to approach this limit.

Figure 9.16 shows the development characteristics for size-classified toner for the Toshiba system. (While the threshold voltage is considerably higher in this figure, it is probable that a bias potential was applied and the true voltage difference at which the threshold occurs is much smaller.) What is particularly interesting about this set of data is that it demonstrates that the voltage width can vary with toner properties such as charge and particle-size distribution. This is consistent with the picture presented in Sect. 9.3 in which it was suggested that the voltage width is partially due to the distribution of toner adhesion.

Finally, we show data [9.31] taken on an experimental setup partially based upon components from a commercially available magnetic monocomponent development system which demonstrate and compare the effects of magnetic and nonmagnetic toner and the application of ac voltages. The development system was mounted so that M/A of the developed toner could be measured. This was done (1) in the standard configuration (magnetic monocomponent development), (2) with the magnet opposite the development zone removed, simulating nonmagnetic monocomponent development, and (3) with and without V_{ac}. The data, shown in Fig. 9.17, demonstrate several interesting effects. The threshold clearly shifts to lower values with the magnets removed.

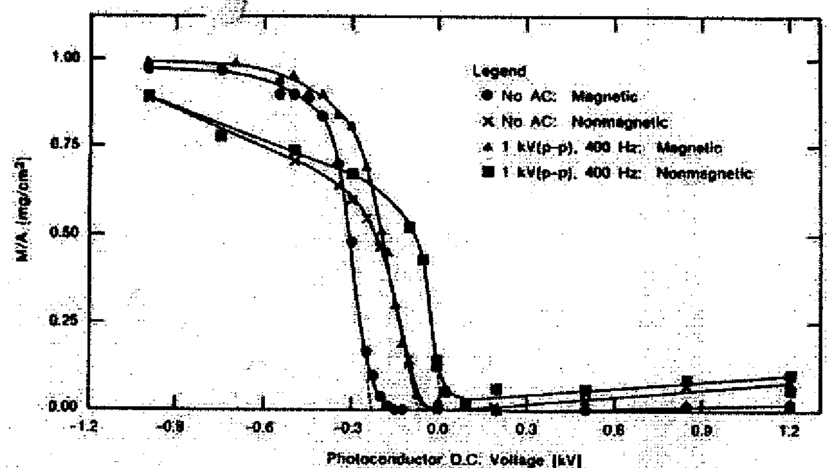


Fig. 9.17. Data for M/A taken on an experimental monocomponent development system. The effect of nonmagnetic toner is simulated by removing the magnets from the development zone. Also shown are data with and without the ac field [9.31]

Also the application of an ac voltage lowers the threshold. Both effects are predicted by the model given in Sect. 9.3. Unexpected is the effect of removing the magnets on the maximum toner development. It decreases the maximum development, at least over the range of voltages measured. One could imagine that the magnets may play a role in breaking the toner-roller adhesive bonds. As the toner moves past the poles, reforming chains, its contact with the roller surface is momentarily broken, decreasing adhesive forces. The magnets also play an important role in preventing the development of wrong sign toner in reverse bias. Note M/A increases with positive bias when the magnets are removed. Measurements of toner charge (not shown) indicate this is due to wrong sign toner.

9.7 Summary

It has always been clear to electrophotographers that the monocomponent development system is simpler than two component, yet successful implementation was not achieved until 1980 with Canon's magnetic insulative development system. The solution to the problem of charging and transporting toner in a monocomponent development system slowly evolved, with many ideas preceding the Canon work. Today this area of electrophotography represents one of intense activity, as can be judged by recent papers and patents. It is an area like many in electrophotography in which success is achieved only with a truly interdisciplinary approach. The increased contact charging sensitivity

of the toner, brought about by the introduction of charge control agents, was clearly a crucial element in producing a viable system.

Today, there appear to be two successful variants of the monocomponent development system under development. Canon's, which uses magnetic insulating toner, and Ricoh's and Toshiba's, which use nonmagnetic insulating toner. All have made compromises. For example, the Canon toner is more complicated than two component toner because it requires the addition of magnetic material. Nonetheless, Canon has successfully used this system commercially in an enormous speed range, from 6 to 70 cpm (Table 1.1). So far Ricoh has produced a development system that works only at a very low speed, 8 cpm. It remains to be seen whether the system is viable at higher speeds. Perhaps most interesting, it has yet to be established whether monocomponent development systems can displace two component magnetic brush development. While monocomponent systems have a manufacturing cost advantage, they must also compete in the areas of reliability and copy quality.

10. Liquid Development

The most prevalent method of liquid development uses the phenomenon of electrophoresis. In electrophoretic development systems, charged particles, suspended in a nonconductive dielectric liquid, move in response to the electric fields of the latent image. Other liquid development techniques besides electrophoresis are described in Sect. 2.3.4, but none have been commercially implemented.

Electrophoresis has been used as an electrodeposition technique since the early part of this century. Its application to electrophotography was suggested independently by *Metcalfe* [10.1,2] and *Mayer* and co-workers [10.3]. In 1955, Metcalfe described liquid development of selenium plates exposed with x-rays. Xeroradiography, a medical x-ray diagnostic tool, was identified early as a potential application of electrophotography (Fig. 9.5). Metcalfe argued that liquid development combined the best features of the other two known development systems: the high contrast, sharp line images of cascade development (Chap. 5) and the excellent halftone images of electroded powder cloud development (Sect. 9.1). In 1957, *Straughan* and *Mayer* [10.3] used a liquid development system in the first electrophotographic printer based on selenium plates addressed by a cathode ray tube. This work was followed up [10.4] at Battelle in 1958 (for preparing transparencies) and RCA in 1960 (for making five color maps on Electrofax paper). One of the first copiers to use liquid development was introduced by SCM corporation. It made 10 copies per minute on zinc-oxide-binder paper. The most commercially successful copiers using a liquid development system were those manufactured by Ricoh (and sold in the U.S. as Savin copiers) that resulted from an international collaboration between Metcalfe's group in Australia, Ricoh of Japan, Kalle of Germany, and Nashua and Hunt Chemical of the U.S. (An interesting account of this collaboration can be found in [10.5]). Ricoh was successful (Sect. 1.1) because they produced a slow but small, inexpensive and reliable copier, a market ignored by Xerox during the 1970s. Liquid development has also been used to develop images created by ionography (Sect. 1.4.2). An example is the Versatec configuration in which the latent image is formed on dielectric paper by applying a voltage sufficient to cause air breakdown to the styli of a multistylus array. This printing process has been given a special name (electrography or direct electrophotography) because light and the photoreceptor are eliminated from the electrophotographic process. As mentioned in

10.5 Summary

Liquid development is a technically viable alternative to powder development and has several distinct advantages, including sharper images (Fig. 3.11) and the potential of high quality color. In addition, its hardware simplicity has certainly been demonstrated in the many commercially available low cost, low speed special paper copiers.

For solid area line development first-order theories exist that have been validated experimentally. A qualitative or semiquantitative understanding of other physical and chemical complexities also exists, including consideration of space charge effects, macroscopic fluid flow, toner depletion effects, and particle interactions. From these theories, one can make reasonable guesses of optimized toner properties, and toner characterization techniques of varying sophistication have evolved.

However, the technical difficulties in implementing this development system are clearly materials related. Additives are required to charge the toner. Maintaining the charge over time and keeping conductive contaminants out of the liquid developer are challenging problems that have obviously been solved in existing machines, but are not discussed in the literature. Furthermore, methods of keeping the background development low while producing good black images are required, just as in powder development. And just as in powder development, almost no information is available on the mechanisms of background development.

Perhaps the most challenging problem for liquid development involves the carryout of the liquid on the paper. As these liquids are usually organic solvents, TLV (threshold limit values) and EPA permitted total emission limits must be met. Such limits can be met with very slow speed machines (as in the Eastman Kodak pre-offset proofing system) or with occasional use of higher speed machines. Advances in this area would significantly increase the use of liquid development systems.

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Chapter 1

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Chapter 2

The interested reader will find books and review articles on electrophotography in [2.1–18]. In addition, many important papers have been presented and published in the proceedings of the IEEE-IAS Annual Conferences, the SPSE International Electrophotography Conferences, and the SPSE International Congresses on Advances in Non-Impact Printing Technologies.

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